POLARIZATION SWITCHING AND DIELECTRIC PROPERTIES OF PZT STRUCTURES

MICHAEL MALETO, EUGENY PEVTSOV, ALEXANDER SIGOV, and ANASTASIA SVOTINA
Moscow State Institute of Radioengineering, Electronics and Automation
117454, Moscow, Russia

We have taken an extensive investigation of ferroelectric structures based on $Pt/PbZr_{0.53}Ti_{0.47}O_3/Pt/Ti/SiO_2/Si$ (PZT) thin films. Such characteristics as D-E hysteresis loops, C-V and V-I curves, polarization pulse switching, and pyroelectric coefficient were examined in the temperature range between 20...200^oC. The effects of interface layers and of the process of charge transfer on the dielectric behavior of the ferroelectric thin films were studied as well. Appreciable asymmetric capacitance-voltage curves and hysteresis loops behavior have been observed for some specimens. These results provide an explanation for the model, which describes the PZT structure as a series circuit of three depletion layer capacitors. Following this method for the high field voltage, one can obtain the values of associated parameters, such as the depletion layer capacitance, bulk permittivity, and space-charge density.

Keywords: ferroelectric films, polarization switching, pyroelectric hysteresis, capacitance-voltage characteristics.

I. INTRODUCTION

Integration of active dielectric materials in microelectronics was very intensive last decade. It gave rise to a new generation of microelectronic devices, such as uncooled pyroelectric arrays, microelectromechanical systems, non-volatile random access memory, microwave integrated circuits [1]. Our research group applied first attempts in this field in the early nineties, beginning from the works dealt with the technology of ferroelectric thin films integrated with silicon CMOS structures. Consequently, the importance of the

investigation of the electrophysical properties of ferroelectrics is beyond question. This paper presents some our developments in this area, which were carried out during last decade. Our main concern in the present work was to develop and improve the basic ideas of the combined approach to some electric measurements of ferroelectric films proposed by earlier [2,3].

Multifunctional measuring system for ferroelectric thin films (MMSFF) under our design differs from analogous ones by its open architecture. This opens a possibility for the explorers of easy and low cost changing its configuration. MMSFF is quite adopted with hardware and software of the leading companies in the field of measuring technique and systems of data acquisition.

The examined specimens were $Pt/PbZr_{0.52}Ti_{0.48}O_3/Pt/Ti/SiO_2/Si$ (PZT) multilayer structures on silicon substrates with SiO_2 interlayers fabricated by the sol-gel technology from colloidal solutions produced by the electrochemical synthesis in methylcellosolve (see Ref. [4]). The film thickness was 0.2...0.3 μm.

II. MEASUREMENTS OF HYSTERESIS LOOPS AND REMANENT POLARIZATION

The simplest method of ferroelectric film properties investigation is the well known Sawyer-Tower procedure. It is important in this case to eliminate the shunt influence of measuring amplifier, i.e. to use circuits with very high input impedance. This is especially important for the case of low frequency (less than 100 Hz). As an alternative it is possible to propose the measurement of the current in reference resistance with subsequent integration.

However, the comparison of hysteresis loops, obtained by these two methods reveals some differences. That is connected evidently with an existence of intrinsic leakage in the film at the measurement frequency. Really, the expression for the current value I at a series resistor can be given as: $I=[C+V(dC/dV)]dV/dt+VG$, where C and G are correspondingly the non-linear sample capacitance and conductivity, V is the applied voltage. Under the integration, the linear part of conductivity can be taken into account on the base of closed charge loop consideration, the influence of higher-order terms leads to the hysteresis loop expansion. Such an estimation of the linear part yields about 1.5 mS.

For applications it is important to know the remanent polarization dependence on applied depolarizing voltage. Two methods

were used for its evaluation. In the first method we used the nonsymmetric hysteresis loops, while in the second method the pulse switching of remanent polarization was used. One can see a good agreement between the data obtained by both methods (see Ref. [5]).

III. VOLTAGE-CAPACITANCE CHARACTERISTICS

As the hysteresis loops represent integrally the result of external electric field action, they also must contain the information on capacitance-voltage characteristics for the differential capacitance. The shape of of C-V characteristics of PZT films for 1 V/s linear sweep voltage only slightly depends on test signal frequency in the range of 0.1-1000 kHz. To establish the connection between hysteresis loop and C-V characteristics we used the Sawyer-Tower method, applying to the sample the sweep voltage nonsymmetric with respect to zero. The differential capacitance value was determined according to the slope of the loop part, when the polarization pulse switching came to an end, i.e. at the beginning of the sweep voltage reverse. The values of differential capacitance for positive and negative nonsymmetric loops calculated by this method show the good correlation with the results of direct measurements by LRC-meter (see Figure 1).

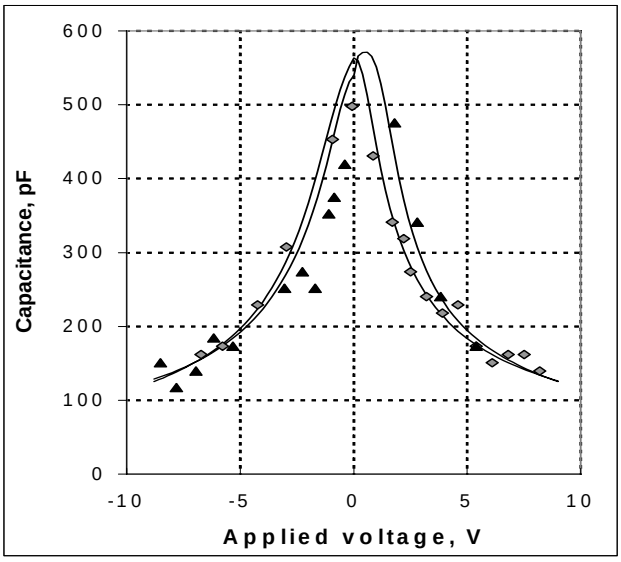

FIGURE 1. C-V characteristics of PZT structure: results of direct measurements and calculated curves based on the derivatives of nonsymmetric hysteresis loops.

A good agreement of these data stimulated attempts of making the hysteresis loop reconstruction, excluding the component caused by a

nonlinearity of the dielectric constant. For this purpose we subtracted the curve of the direct voltage-capacitance characteristic measurement from the result of differentiation of the initial hysteresis loop, and reconstructed the hysteresis loop again by the integration. The results obtained are discussed in detail in Ref. [6].

The effects of interface layers and of the process of charge transfer on the ferroelectric thin films dielectric behavior were studied. A specific model taking into account interface layers close to metal electrodes has been suggested. These procedures have been used for investigation PZT structures. Appreciable asymmetric capacitance-voltage curves and hysteresis loops behavior have been obtained for some specimens. These results provide an explanation for the model which describes the Pt/PZT/Pt structure as a series circuit of three depletion layer capacitors, according to Schottky diode model (see Ref. [7]). In the case being considered, $1/C^2 \sim k(V-V_F)$ (here V_F is the voltage drop on the ferroelectric itself), and hence the influence of interfacial states, and the voltage drop in the intrinsic ferroelectric can be determined. To explain the electrical asymmetries, we assumed that they came from the interfacial state difference between the top Pt/PZT and the bottom PZT/Pt. Following this method for the high field voltage, we could obtain values of associated parameters, such as the depletion layer capacitance, bulk permittivity, and interface states and space-charge density. An example of this technique is shown in Figure 2.

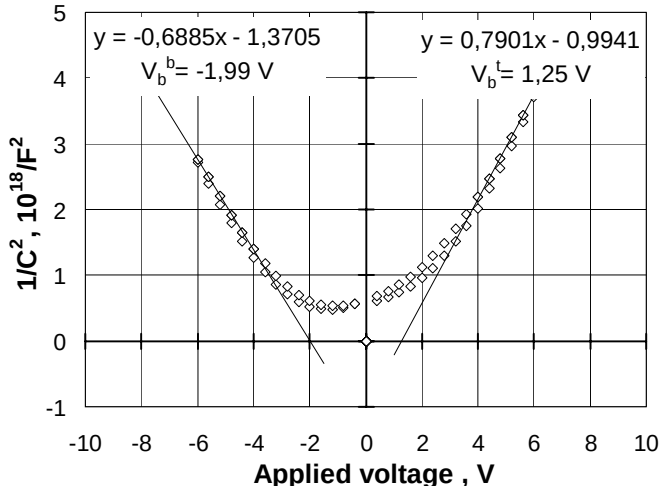

FIGURE 2. The Schottky diode model in the PZT structure. Thin lines denote the results of linear fitting for high field regions (magnitudes of interface states density are in region 0.6...2.2 10^{-19} $1/cm^3$).

IV. VOLTAGE-CURRENT CHARACTERISTICS

Current density for our films with the thickness about 0.2μm was 2nA/cm^2 under applied voltage of 1.0V. But it increases by several powers of 10 under applied voltage of few volts. And one can see current relaxation to a constant value with the time constant of few minutes. The same situation takes place under measuring the short circuit current just after repolarization. In this case the short circuit current decreases to the values less then 1pA within 2-3 minutes.

V. PYROELECTRIC MEASUREMENTS

Pyroelectric properties of the films were studied by low-frequency temperature wave method [5]. These data are generalized in order to obtain the pyroelectric hysteresis loop for the given ferroelectric sample. The proficiency of pyroelectric study should be particularly emphasized because it allows one not only to separate switchable and nonswitchable polarization components but to evaluate the polarization storage conditions easily and reliably. Furthermore, the determination of ohmic constituent of the pyroelectric current provides a way of examination of the free charge behavior in the films. Thus, the pyroelectric methods are an important addition to traditional methods of investigation the mechanisms for conductivity and charge mobility in the films by their voltage-capacitance and voltage-current characteristics.

So it was shown that analog memory could be realized in thin ferroelectric films due to their stable state remanent polarization. The two phenomena pointed out earlier may be used in the devices performing analog multiplication of two signals, one of them is incident radiation, the other is a priori storage information in the form of specially appropriately polarized pyroelectric detector elements. This can produce compensation of non-uniformity of sensitivity in the UFPA elements for the purpose of the spatial noise reduction.

VI. CONCLUSIONS

Developed multifunctional measuring system is useful and effective facility for investigation of physical processes in ferroelectric based structures. It makes possible to carry out determination of basic electrophysical characteristics of ferroelectrics: studying the ferroelectric hysteresis, determining pyroelectric coefficient by static and quasy-static techniques, taking magnitude of remanent polarization,

measurements of dielectric characteristics, measurements of the specimen electrical conductance.

Basing on this measuring system, there were developed several methods which give the opportunity to improve the comprehension of the processes in ferroelectric systems from physical point of view. Combined studies of C-V characteristics, polarization saturation, remanent polarization, and pyroelectric coefficient show that developed and improved methods complete each other and have a good correlation. They may provide experimental data for both theoretical studies and engineering design of various devices. The lead content of the source solutions was optimized as regards to the best parameters of the ferroelectric hysteresis loop, breakdown voltage, and dielectric losses. From the same standpoint, the optimum regimes of heat treatment were chosen as well.

VII. ACKNOWLEDGMENTS

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