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FERROELECTRICITY

Conductivity of Metal–Dielectric–Semiconductor Structures Based on Ferroelectric Films

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Abstract—In this paper, we present the results of experimental studies of the frequency and temperature dependences of the electrical conductivity of metal–dielectric–semiconductor structures based on ferroelectric films of the $Ba_{0.8}Sr_{0.2}TiO_3$ composition. In the temperature range of 290–400 K and the frequency range of 25–10^6 Hz, the conductivity was found to obey the $\sigma \propto f^{0.76}$ law, which is characteristic of the hopping mechanism of charge transfer over states localized near the Fermi level. The density of these states, average distance and time of jumps are estimated.

Keywords: metal–dielectric–semiconductor structures, ferroelectric films, barium–strontium titanate solid solutions, alternate current conductivity

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1. INTRODUCTION

At present, there is a rapid increase in the number of theoretical and experimental studies in the field of SHF devices. There is a modernization and expansion of the application of previously known devices with an increase in operating frequencies, as well as the introduction of new devices based on the achievements of solid state physics and advanced technology. One of the priority areas for the development of SHF devices and energy-independent memory elements is the use of metal–dielectric–semiconductor (MDS) structures with ferroelectric films as insulating layers [1]. The unique physical properties of ferroelectric materials (in particular, the high dielectric constant that changes under the effect of an external electric field) allow creating a virtually new class of information storage and processing devices based on MDS structures [2]. Energy-independent memory elements based on ferroelectric materials are characterized by low-current consumption, a large number of recording cycles, and long time and high reliability of data storage under the impact of external factors. A promising type of ferroceramics for SHF-technology applications is solid solutions of barium–strontium titanate ($Ba_{1-x}Sr_xTiO_3$ or BSTO). BSTO ceramics are currently successfully used in accelerator technology: phase shifters and high-power switches for power supply circuits of linear accelerators, and controlled accelerator structures with dielectric filling. Solid solutions of $Ba_{1-x}Sr_xTiO_3$ have ferroelectric properties at room temperature, and unlike bulk material, the dielectric constant of thin films remains sufficient high and almost unchanged over a wide range of temperatures. Among BSTO solid solutions, the $Ba_{0.8}Sr_{0.2}TiO_3$ composition is characterized by the smallest smearing of the structural phase transition, which makes it the most convenient material for the industrial production of capacitors of integrated circuits and other micro- and nanosystem systems.

Studies of the electronic properties of ferroelectric films have occupied one of the central places in the physics of the condensed state of matter in recent decades. Studying the properties of BSTO ceramics in order to improve the manufacturing technology of the material with the specified characteristics of structures based on it is a very relevant physical problem. The effect of grain size on the dielectric and ferroelectric properties of $Ba_{0.8}Sr_{0.2}TiO_3$ was studied in [1]. The rearrangement of the polarization and other properties of BSTO ferroelectric ceramics when changing the external field was quantitatively studied using microwave measurements [3]. Although, due to its unique properties, BSTO has been long used in the production of optical information carriers, elements of pho-

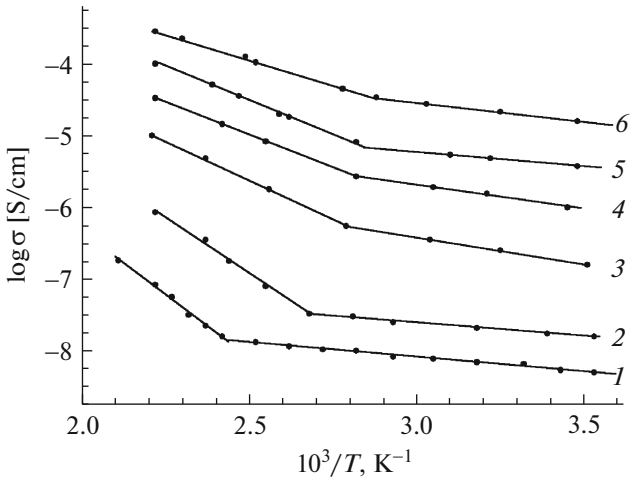

Fig. 1. Temperature dependences of electrical conductivity for $Ba_{0.8}Sr_{0.2}TiO_3$ structures at various frequencies: (*1*) 25, (*2*) 10^2, (*3*) 10^3, (*4*) 10^4, (*5*) 10^5, and (*6*) 10^6 Hz.

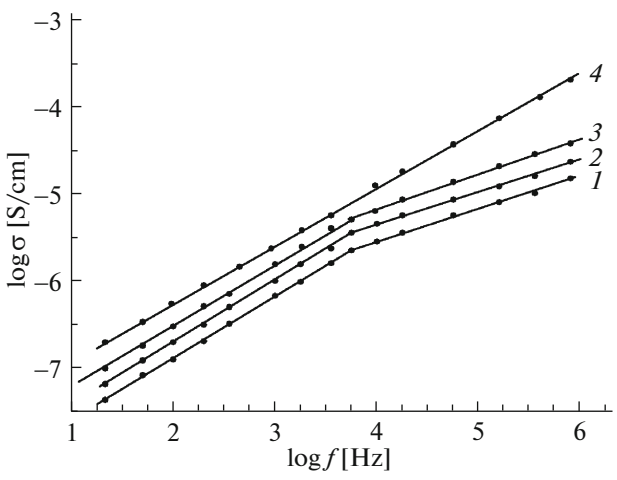

Fig. 2. Frequency dependences of the electrical conductivity of the $Ba_{0.8}Sr_{0.2}TiO_3$ structure at various temperatures: (*1*) 293, (*2*) 373, (*3*) 423, and (*4*) 453 K.

ton technologies and radio electronics [1], the mechanisms of electrical conductivity in this high-resistance material have not been studied in detail. This paper is aimed at studying of charge transfer processes in a ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ film in an alternating electric field.

2. MATERIALS AND EXPERIMENTAL METHODS

Metal–dielectric–semiconductor structures, which were a silicon substrate, a ferroelectric film of the $Ba_{0.8}Sr_{0.2}TiO_3$ composition, and an upper nickel electrode, were fabricated for studies. The ferroelectric layer was grown by high-frequency reactive sputtering of a ceramic target in an oxygen atmosphere using a PLAZMA-50 SE setup according to the procedure presented in [4]. The main idea of the method is to use low-temperature oxygen plasma as a medium, where the oxidation process during deposition prevails over the reduction process. The main advantage of the method is the possibility of spraying structurally perfect ferroelectric films while maintaining oxygen stoichiometry. As substrates, *p*-type silicon of the SDB-20 type with a crystallographic orientation [100] was used. The thickness of the substrates is 200 ± 2 μm. The contacts were formed by the electron beam method through a shadow mask. Nickel was used as an ohmic contact material. The contact area was 2.7×10^{-4} cm^2, and the thickness was 0.1 μm.

The conductive properties of MDS structures were studied using an E7-20 digital impedance meter in a wide frequency range (25–10^6 Hz). For the experiments, samples of ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ films with a thickness of 310 ± 20 nm on silicon substrates in the form of plane capacitors were prepared [5]. The measurements were carried out with a constant voltage drop across the sample of 1 V.

3. RESULTS AND DISCUSSION

An X-ray diffraction study showed that a parallel arrangement of the axes of the film and the substrate in the conjugation plane, i.e., [100]BSTO ∥ [100]*p*-Si, was observed for all the films studied. Figure 1 shows the temperature dependences of the low-signal conductivity σ(T) of ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ films at various frequencies. In the frequency range of 25–10^6 Hz, the plot of logσ vs. $10^3/T$ consists of two lines with different slopes, from which it follows that the electrical conductivity of the ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ films depends thermally on the absolute temperature T [6]. The activation energies E were determined from the slopes of these dependences. Their values decrease with increasing frequency f: from 0.15 to 0.05 eV in the low-temperature region and from 0.75 to 0.35 eV in the high-temperature region. Note that the activation character (with a constant activation energy) of the behavior of σ near room temperature in the frequency range from 10^4 to 10^6 Hz cannot be considered proven since there are insufficient experimental data in this interval (a total of three measurements at each frequency). The frequency dependence of the activation energy can be explained by the hopping mechanism of electrical conductivity [7]. Based on the σ–f plots (see Fig. 2), the experimental data are well described by the following relation:

$$\sigma = Af^s, \quad (1)$$

where A is a constant coefficient characterizing the properties of the sample under study, the exponent s is 0.76 at frequencies below 10^4 Hz and decreases to

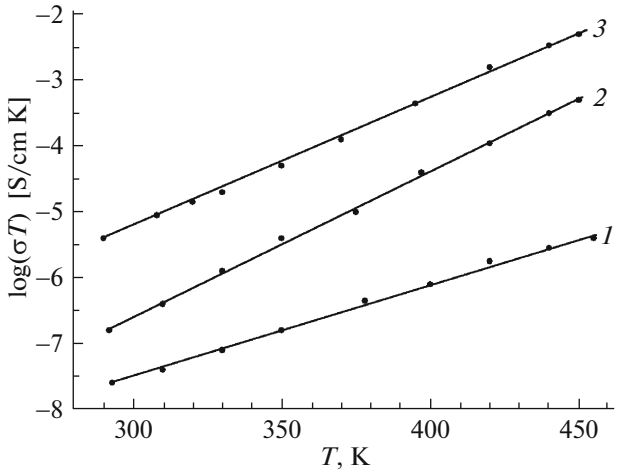

Fig. 3. Dependence of $\ln(T\sigma)$–T of $Ba_{0.8}Sr_{0.2}TiO_3$ films at: (*1*) 10^4, (*2*) 10^5, and (*3*) 10^6 Hz.

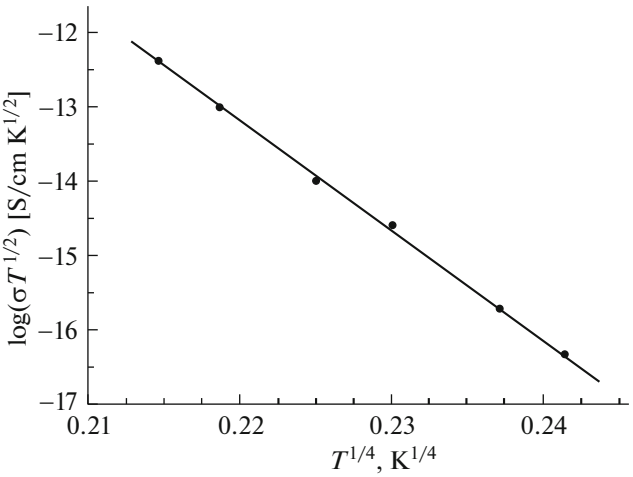

Fig. 4. Temperature dependences of the electrical conductivity of $Ba_{0.8}Sr_{0.2}TiO_3$ films in Mott coordinates.

0.32 in the range of 10^4 Hz $< f < 10^6$ Hz. Note that the frequency dependence of the conductivity (1) is characteristic of the hopping mechanism of electric transfer [7].

An expression with a nonactivation form of the temperature dependence for conductivity σ was obtained in [7]:

$$\sigma(T) = \frac{\Omega}{T}\exp\left(\frac{T}{T_0}\right), \qquad (2)$$

where T_0 is the characteristic temperature, and Ω is the proportionality coefficient. According to formula (2), the combination $\ln(\sigma T)$ should linearly depend on temperature. Figure 3 shows the experimental dependence of $\ln(\sigma T)$–T at various frequencies. This dependence is linear, which contradicts the activation nature, but confirms the hopping mechanism of conduction. The following expression for the frequency dependence of hopping conductivity was obtained in [8, 9]:

$$\sigma = \frac{\pi^4 e^2 k T N_F^2}{48\alpha^5} f\left[\ln\left(\frac{\nu_{ph}}{2\pi f}\right)\right]^4, \qquad (3)$$

where N_F is the density of states localized near the Fermi level, k is the Boltzmann constant, α is the spatial attenuation constant of the localized state of electrons (the representation $\Psi \propto e^{-\alpha r}$, where r is the distance from the localization center to the observation point, is used for the wave function), ν_{ph} is the phonon frequency, and e is the elementary charge. According to expression (3), the conductivity depends on the frequency as $f[\ln(\nu_{ph}/f)]^4$ while, at $f \ll \nu_{ph}$ ($\nu_{ph} \approx 10^{12}$ Hz), the term in square brackets is well approximated by the dependence $f^{-0.2}$, which practically leads to the coincidence of the experimental dependence (1) with relation (3). Using formula (3) for the values $\alpha = 1.5$ nm and $\nu_{ph} = 10^{12}$ Hz, the density of states at the Fermi level $N_F = 4.5 \times 10^{19}$ eV^{-1} cm^{-3} was determined from the experimental function $\sigma(f)$.

For a number of studied samples, the temperature dependences of conductivity below 400 K were straightened in the Mott coordinates as $\log\sigma$–$(1/T)^n$ at $n = 0.25$. This indicates the conductivity with a variable hopping length, which is described by the following relation [10, 11]:

$$\sigma(T) = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)^n\right], \qquad (4)$$

where σ_0 is the conductivity as $T \to \infty$; $T_0 = 16/N_F k\alpha^3$ is the characteristic temperature; n is an power index characterizing the conduction mechanism with variable activation energy ($n = 0.25$ for the Mott mechanism [7] and $n = 0.5$ for the Shklovski–Efros mechanism [10]). The experimental temperature dependence of the conductivity of the $Ba_{0.8}Sr_{0.2}TiO_3$ layer at $f = 10^4$ Hz is shown in Fig. 4 and indicates the predominance of the Mott mechanism. According to the theory of hopping conductivity on alternating current, the average hopping distance (R) is determined by the following formula [8, 9]:

$$R = \frac{1}{2\alpha}\ln\left(\frac{\nu_{ph}}{f}\right). \qquad (5)$$

For the studied ferroelectric films, the value of R was 10 nm. The relationship between the length and frequency of the hopping is given by the following expression:

$$\tau^{-1} = \nu_{ph}\exp(-2\alpha R). \qquad (6)$$

Hence, τ = 10 ns for the average time of charge carrier jumps from one localized state to another.

4. CONCLUSIONS

An analysis of the results allows concluding that the conductivity of ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ films in the studied temperature range are mainly realized by the hopping mechanism. The temperature and frequency dependences of the electrical conductivity indicate the possibility of realizing the conductivity with a variable hopping length on localized states near the Fermi level.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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