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Resistive memory effect in a thin-film structure based on $YBa_2Cu_3O_{7-x}$ superconductor

Abstract. *The paper presents results of the experimental research in which the electro-resistance memory effect have been observed in a thin-film structure based on a high-temperature $YBa_2Cu_3O_{7-x}$ superconductor exposed to electric current and an attempt to interpret the physical mechanism of that effect based on the processes of oxygen ion or electron trapping.*

Streszczenie. *W pracy przedstawiono wyniki badań doświadczalnych, w których zaobserwowano elektrorezystancyjne zjawisko pamięci w strukturze cienkowarstwowej opartej na nadprzewodniku wysokotemperaturowym $YBa_2Cu_3O_{7-x}$ poddanym działaniu prądu elektrycznego, oraz przeprowadzono próbę interpretacji mechanizmu fizycznego tego zjawiska w oparciu o procesy pułapkowania jonów tlenu albo elektronów.* ***(Zjawisko pamięci rezystancyjnej w cienkowarstwowej strukturze na bazie nadprzewodnika $YBa_2Cu_3O_{7-x}$).***

Keywords: high-temperature superconductors, resistive memory effect, electro-resistance effect, current and temperature characteristics.
Słowa kluczowe: nadprzewodniki wysokotemperaturowe, zjawisko pamięci rezystancyjnej, zjawisko elektrorezystancyjne, charakterystyki prądowe i temperaturowe.

Introduction

A race, present in electronics for many years, to obtain larger and larger operating memory capacities in computers faces more and more difficult barriers for development. Traditional random access memories (RAM), based on semiconductor materials, have practically reached the limit of their physical capabilities to reduce dimensions and energy necessary to record/ read out information and, in consequence, the capabilities to increase capacity. Therefore, intensified research activity can be observed in recent years to search for new materials and mechanisms that can be used for development of RAM components. One of such materials are high-temperature superconductors (HTS). Superconductor materials have been enticing researchers for many years due to their low energy losses and quick reaction time. On the other hand, which is considered to be their greatest fault, the necessity of cooling them becomes less and less troublesome as technology develops.

Memory effects in HTS-based structures have been studied by many scientists [1-10]. A part of the observed effects are of a magnetic nature. They are based on the magneto-resistance effect [1,2], Josephson junctions [3], or Josephson vortices [4]. In papers [5,6], in turn, optical memory effects in high-temperature superconductors are presented. In numerous other studies electro-resistance memory effects have been observed [7-10].

The purpose of this paper is to present experimental research, in which the resistive memory effect have been observed in a thin-film structure based on a high-temperature $YBa_2Cu_3O_{7-x}$ superconductor exposed to electric current, and an attempt to interpret the physical mechanism of that effect.

Experiment

For purposes of this paper a sample in the form of a HTS structure consisting of a thin-film $YBa_2Cu_3O_{7-x}$ superconductor deposited onto a sapphire substrate (Al_2O_3) of 10x6 mm was examined. The superconductor film with the thickness of $h \approx 0.5$ μm was obtained by means of magnetron sputtering. Crystallographic examinations revealed a dominant orientation of the crystallite c-axis perpendicular to the film plane [11]. Then, the HTS film was shaped using the photolithography method into a microbridge with the width of w=200μm and the length of l=2 mm, and then the silver contact layers were applied and shaped.

Parameters of the HTS microbridge measured immediately after it was formed amounted to: critical temperature T_c=87.5 K, superconducting transition temperature width ΔT_c=1.4 K and critical current $I_c \approx 550$ mA at the temperature of 78 K [11].

The examined sample was placed in a liquid nitrogen continuous-flow cryostat intended for measurements within the temperatures ranging from 77 to 300 K, and fastened to a cold finger with silver paste. During the measurements the sample remained in a vacuum of 10^{-2} hPa. Measurements of the microbridge resistance were carried out using the 4-wire method, supplying it with current from a source operating at the current stabilization mode. The current was passed in one direction only, and its value was changed within the range from 0 to 20mA, that is much below the critical current level I_c.

Measurement results and their analysis

The measurements were carried out with cyclical change of the current and the temperature. The results obtained in the experiments are presented in Figures 1 and 2. The sequence in which the measurements were performed was consistent with numeration of the curves and the direction of arrows marked on them. Temperature dependences shown in Figures 1a and 2a, as well as starting and final points of the current characteristics (Fig. 1b and 2b) were obtained while the sample was exposed to a very low conduction current amounting to 10 μA. In Figures 1b and 2b the curves of current characteristics obtained at the ambient temperature of $T_a \approx 300$ K are marked with a solid line, and curves of current characteristics obtained in the liquid nitrogen temperature of $T_{LN} \approx 78$ K are marked with a dotted line. In the inset of Figure 1b its magnified fragment is presented.

The first measurements were carried out at low currents (up to 2 mA). The runs of characteristics were reproducible both at ambient temperature and at T_{LN}. An example of such a dependence at T_a is curve 1 (Fig. 1b). While being affected by the 2 mA current, the HTS microbridge resistance decreased by approx. 20%. After it was cooled to 78 K the resistance rose 3.5 times, and when the temperature was increasing while determining the $R(T)$ characteristic – the resistance fell by 72% to the same level of 640 Ω as before cooling (curve 2). Negative values of the temperature resistance coefficient (α_T) prove the occurrence of thermo-activated electric conductivity mechanism, which is characteristic of dielectrics. Repeated cooling of the sample brought about an increase in the microbridge

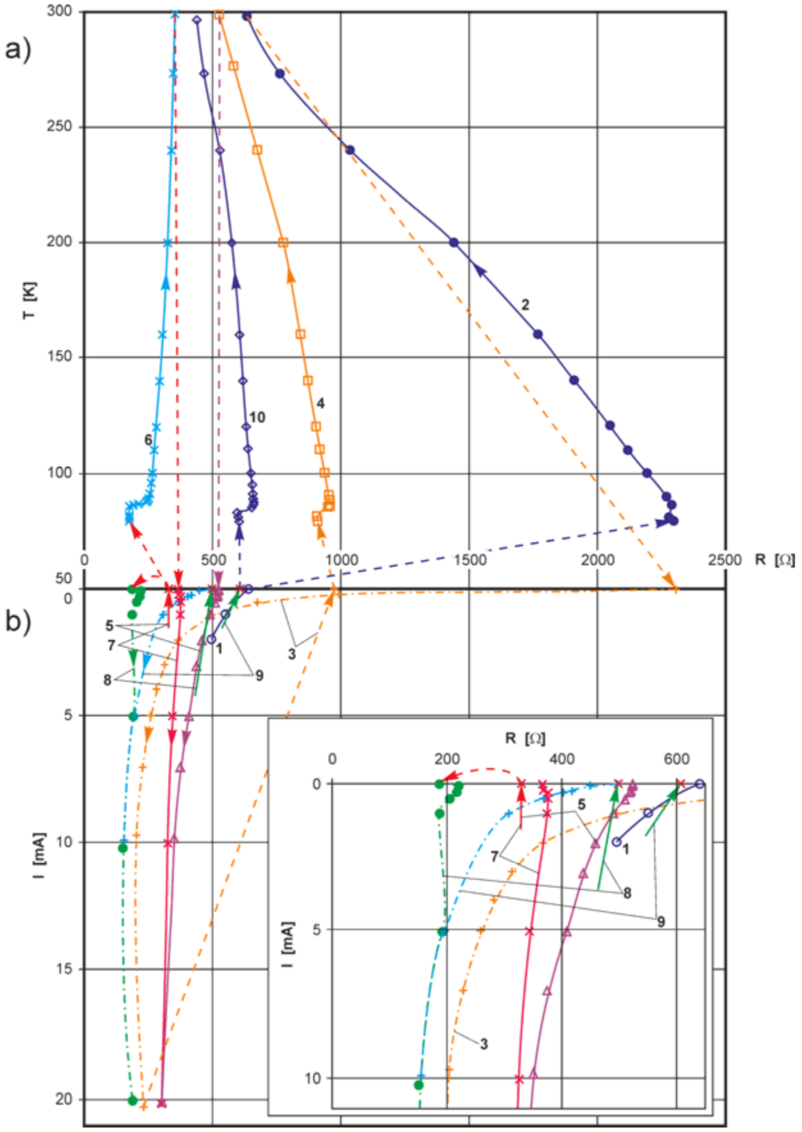

Fig.1. Temperature (a) and current (b) dependences of the HTS microbridge resistance in successive cycles of current interactions and temperature changes. Numeration of the curves corresponds to the sequence of measurement cycles. In Figure b) curves of current characteristics obtained at the temperature of T=300 K are marked with a solid line, and those obtained at the temperature of T=78 K with a dotted line. The inset shows a magnified fragment of Figure b)

resistance to the previously obtained value of 2300 Ω. In further part of the experiment the current flowing through the microbridge was increased to 20 mA (curve 3 in Fig. 1b). That time the resistance fell to 230 Ω (by 90%). However, after the current was turned off, it increased to 970 Ω. Afterwards, the temperature characteristic of the sample was determined (curve 4 in Fig. 1a). The character of that dependence (α_T<0) informs us that the microbridge was still in the dielectric state, though its resistance decreased in relation to curve 2. In the next stage the microbridge was exposed to current at ambient temperature (curve 5). Its resistance fell to 300 Ω first, and after the current was turned off it rose to 350 Ω, though it did not reach the initial value (before the microbridge was exposed to current). When the sample was cooled to 78 K the *R(T)* temperature characteristic of the microbridge resistance was determined again (curve 6). It turned out that its character was completely different than it had been last time, i.e. typical of a superconductor. With the rise of temperature to 85.9 K, the resistance practically remained at an invariable level of 175Ω, and then there was a jump to 255 Ω and further monotonic growth. The observed jump in the resistance corresponds to transition of the microbridge (or its part) from the superconducting state (S) to the normal state (N). The resistance growth in the normal state (at T>87.5 K) has a typically metallic character (α_T>0). The repeated passage of current at ambient temperature (curve 7 in Fig. 1b) results in the changes of R similar to the changes in curve 5. In the further course of the experiment the sample was cooled to T_{LN} again and expose to current twice: first to 20 mA (curve 8), and then to 10 mA (curve 9). The cooling brought about transition of the microbridge to the S state (R≈190 Ω), and the flow of higher and higher current resulted in the fall of resistance by approx. 19% (at I=10 mA) first, and then the rise to the initial value of 190 Ω (curve 8). When the current was turned off, the microbridge resistance unexpectedly increased to 500 Ω, in order to rise to 600 Ω after the next current cycle (curve 9). The temperature characteristic determined afterwards (curve 10) demonstrated transition of the HTS film to the dielectric state. In further stages of the experiment (Fig. 2), the HTS microbridge was alternately exposed to current at ambient temperature (Fig. 2b) and after cooling it to 78 K temperature characteristics were determined (Fig. 2a). After the first current cycle (curve 11) the resistance decreased by approx. 28%, and after cooling it turned out that the bridge returned to the superconducting state (curve 12) with even lower resistance of 110 Ω. The subsequent current cycles (curves 13 and 15) brought about results analogical to the previous ones at the same temperature, and the temperature characteristic (curve 14) proves that the microbridge still remains a superconductor.

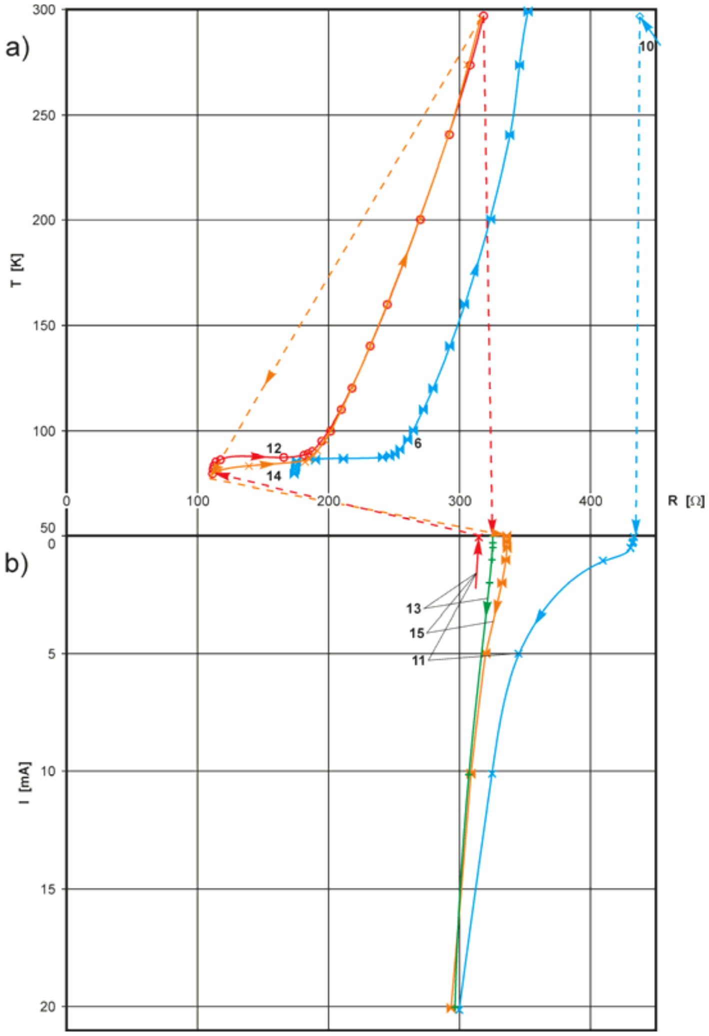

Fig.2. Temperature (a) and current (b) dependences of the HTS microbridge resistance in successive cycles of current interactions and temperature changes. Numeration of the curves corresponds to the sequence of measurement cycles. The curves of current characteristics in Figure b) were obtained at the temperature of T=300 K

The presence of relatively high residual resistance of the superconductor, R_S (initial parts of curves 6, 12, 14 in Fig. 2a) may result from the fact that not all segments of the microbridge pass to the S state at T_{LN} because of its material inhomogeneity. Inhomogeneity is very probable in case of long bridges, and such a bridge was used in the experiment (*l*=2 mm). The superconductor properties also changed during the experiment, which can be assumed based on the change of parameters of the S↔N transition. Whereas for curves 6 and 12 the critical temperature T_c and the transition width ΔT_c are approximately equal: 87.5 K and 1.4 K respectively, for curve 14 they amount to 85.5 K and 3.7 K, which means that the quality of the HTS film deteriorated.

The results of measurements obtained in the study allow to conclude that the exposure to current at ambient temperature (curves 5, 7 in Fig. 1b and 11, 13, 15 in Fig. 2b) leads to a fall in the resistance of the HTS microbridge and its further transition to (or preservation of) the superconducting state. Analogical impact of current at the liquid nitrogen temperature (curves 3, 8, 9 in Fig. 1b) results in the rise of resistance after the current has been turned off and transition of the bridge to (or preservation of) the dielectric state. The changed resistance values are stable in time, therefore they may be treated as non-volatile memory states. The factor bringing about changes in these states is the conduction current (or the electric field), thus the observed effects can be classified as the electro-resistance memory effect.

Similar behaviour of thin films of high-temperature superconductors, and also other materials with the crystal structure of perovskite has been observed by many authors. Usually it has been interpreted in categories of oxygen ion diffusion [7,10,12-15]. The external electric field causes diffusion of O^{2-} ions because they are weakly bound with the crystal lattice. It passes through a relatively big number of oxygen vacancies. These ions are seized by trapping centres located mainly near boundaries of thin films, crystallites or crystal structure defects (e.g. dislocations). Ions located in traps form spatial charge areas that attract free carriers (in HTS these are holes), which in turn results in decreased concentration of charge carriers in the material and increased resistance of the microbridge. After changing direction of the electric field oxygen ions can be released from the traps and diffuse in the opposite direction, which leads to a fall in the resistivity of the material. Processes of O^{2-} ion diffusion and their release from the trapping centres have a threshold character, which means that they require certain activation energies. The mechanism described above has a bipolar nature and leads to the appearance of a hysteresis loop on the current and voltage characteristic of the micribridge, which can be applied for building RAM memory cells.

Nevertheless, in our study changes in the resistance state of the microbridge occurred in both directions at the same direction of the current flow. In paper [8] the electro-resistance memory effect was explained using the mechanism of electron, not oxide ion, trapping. During the flow of current in the HTS film some electrons are seized by electron traps located in the crystal lattice. This way an uncompensated spatial charge appears, which plays a role of a floating gate in a structure analogical to a field-effect transistor. Such a bound charge subsequently induces additional carries (holes), which results in increased conductivity of the material, similar as in the mechanism of O^{2-} ion trapping. Probability of electron trapping depends on their energy (and in consequence on the magnitude of the current or the electric field). When the currents are too low trapping does not occur because the energy of electrons is not sufficient to overcome the energetic barrier of the trap, and, on the other hand, when the currents are too high, electrons are released from the traps, which leads to a fall in the HTS conductivity. This mechanism of resistance switching does not depend on direction of the current flow, thus it has a unipolar nature – as it was determined in our study. Nevertheless, explanation of our findings by means of the electron trapping mechanism would be premature for the time being. In order to do so further studies, both experimental and theoretical, are necessary.

Summary

The results of the experimental research presented in the paper prove the existence of the electro-resistance memory effect in the thin-film structure based on the high-temperature $YBa_2Cu_3O_{7-x}$ superconductor. The physical mechanism of this effect is not completely comprehensible. That is why there is a need to conduct further studies, both experimental and based on mathematical modelling, in order to explain the electro-resistance memory effect and determine an optimal structure and modes of controlling RAM memory cells, which could be based on HTS structures.

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