YBCO and LSMO nano-films and sandwiches prepared by magnetron sputtering

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Abstract. DC and RF magnetron sputtering techniques were used for growing nano-films (t<100 nm) of high temperature superconducting (HTS) YBa2Cu3O7 (YBCO) and ferromagnetic (FM) manganite La0.7Sr0.3MnO3 (LSMO) materials on LaAlO3 (LAO) and Al2O3 (ALO) substrates as well as for preparing of single-, double- and three-layer structures in different areas of the same substrates. The procedure allowed growing of structures on LAO substrates where the critical temperature of YBCO thin film components was more than 84 K. The LSMO films grown ALO substrates were ferromagnetic while the YBCO films grown on LSMO/ALO did not demonstrate superconductivity.

1. Introduction
Structures consisting of oxide high temperature superconducting (HTS) and ferromagnetic (FM) nano-films (with the thickness t<100 nm) are a very intensive research field nowadays [1-5]. Such systems constitute attractive model systems for investigating the interplay between two fundamental condensed-matter phenomena, ferromagnetism and superconductivity [1-5]. On the other hand, the FM/HTS heterostructures are perspective for application in the conventional devices and in the devices of spintronics [6]. Polycrystalline manganite films, physical properties of which are modified due to the grain boundary effect [7,8], become attractive candidates for the device applications as well. For these reasons, the growth of YBCO and LSMO single and multi-layer on different substrates and their electrical and magnetic characterization is important for the development of hybrid HTS/FM devices. In this paper we report the results of preparation and investigation of epitaxial single- and three-layer thin film structures of HTS YBa2Cu3O7 (YBCO) and FM La0.7Sr0.3MnO3 (LSMO) materials on LaAlO3 substrates and of polycrystalline layers of these materials on Al2O3 substrates.

2. Experimental
The RF and DC magnetron sputtering systems were used for in-situ growing of HTS YBCO and FM LSMO nano-films and double- and three-layer FM/HTS structures on LaAlO3 (LAO) and Al2O3 substrates.
For obtaining YBCO/LSMO/YBCO three layer structures, after the deposition of the bottom YBCO1 layer by DC magnetron sputtering, the sample was transported into the RF magnetron system, where a deposition of LSMO layer was performed. Afterwards the sample was transported back to the DC magnetron system and the final top YBCO2 layer was sputtered. The deposition conditions were close to those used in [9]. Masks, prepared from the stainless-steel-foil, were used during the deposition process to form the “shadowed” areas of the sample, free of the YBCO or LSMO components. Three factors affect negatively the sample quality in such a technology: 1) the preparation of a sequence of YBCO and LSMO layers in two different installations requires additional cooling and heating processes which cause strains and deformations in the sample; 2) during the transportation process the sample contacts with ambient atmosphere and its surface is polluted by microparticles; 3) the masks made from metal foil can affect the temperature balance in the substrate and the components of the mask material can diffuse into the sample.

The electric resistance of YBCO films was investigated using a four-probe method. The small drive and receive coils were used for investigation of the AC screening properties (at ~1 kHz) and the critical temperature \( T_C \) of the samples. In such a configuration the drive coil induces the shielding current in the film area with the diameter ~5 mm and the signal induced in the receive coil reflects information concerning such local area of the sample. The magnetic state of the LSMO film was confirmed using the magneto-optic (MO) visualization technique, which reveals the perpendicular component of the magnetic induction created by FM domains or domain walls [10] in the film.

3. Results and discussion

3.1. Parameters of YBCO and LSMO films on LAO and ALO substrates

Electrical parameters of YBCO films with the thickness \( t > 25 \) nm prepared on LAO substrates were of the same order (the critical temperature \( T_C \sim 88-91 \) K, the critical current density \( J_C \sim 0.9-2 \) MA/cm\(^2\) at 77 K) with those of the YBCO films of conventional thickness (>100 nm). Some worsening of the parameters of YBCO films were observed in thin YBCO/LSMO structures due to the technological features of preparation of such structures and to an interaction of HTS and FM layers [9].

Single LSMO nano-films prepared on LAO substrates were in the FM state in the investigated temperature interval (7 – 340 K) and demonstrated a presence of FM domain structure. The configuration of the domain structure depended on the external magnetic field intensity, the field orientation and the sample prehistory and it was possible to observe an irregular domain structure (figure 1a) with out-of-plane magnetization of domains, a strip domain structure (grown on the twinned areas of the substrate - figure 1b) and some zigzag-like domain walls separating domains with the anti-parallel orientations of the magnetization (figure 1c). Domain structures of similar type were observed in double layer LSMO/YBCO structures [11] as well.

LSMO nano-films, deposited directly onto ALO substrates were in FM state at the room temperature. This was confirmed by attraction of pendulous samples by a permanent magnet. Image of the edge area of the sample, obtained by magneto-optic visualization technique, demonstrated a brightness contrast due to the FM state of the sample as well. Patterns of the domain structure were not observed clearly in these samples. We suppose that our samples grown on ALO were polycrystalline
and consisted of very small grains (as in the case of La_{0.7}Ca_{0.3}MnO_3 films grown on Si substrates or LSMO composite films [7,8]). The magnetic inhomogeneities along such samples could be of very small dimensions and not be "observable" because of the not enough space resolution of MO method.

The LSMO nano-films showed high electrical resistance $R$ and temperature dependence of the resistance was characterized by two peculiarities: the metal-insulator transition temperature was lower than the Curie temperature of LSMO material and the upturn of the resistance $R$ was observed at low temperatures (figure 2, curve1). Similar behavior of $R$ vs $T$ dependence was observed earlier in polycrystalline LSMO-ALO composite materials and films [7,8] and was interpreted as due to a parallel existence of several kinds of electronic conduction channels in them. It is interesting to note also, that an additional YBCO layer deposited on the top of LSMO film was not superconducting and led to a total modification of $R$ vs $T$ dependence of the sample (figure 2, curve 2).

![Figure 2](image_url)

**Figure 2.** Temperature dependence of the resistance of a 40 nm thick LSMO film (curve 1) and a (YBCO-60nm)/(LSMO-40nm) double layer (curve 2) deposited directly on Al_2O_3 substrates.

![Figure 3](image_url)

**Figure 3.** YBCO/LSMO/YBCO three-layer structure and the positions of the contacts (P1-P5), used in 4-probe measurements of the resistance. The circles – the sample areas measured by contactless AC method.

3.2. Electric characteristics and AC response of YBCO/LSMO three-layers grown on LAO substrate. Configuration of a (YBCO-70nm)/(LSMO-20nm)/(YBCO-70nm) three-layer structure grown onto 10 mm x 10 mm LAO substrate is schematically shown in figure 3. It contains the areas with the single YBCO2 layer, with the double YBCO2/YBCO1 and YBCO2/LSMO layers and a three-layer (YBCO2/LSMO/YBCO1) area.

The temperature dependences of the resistance $R$ measured by four probe method for the different positions of the contacts (figure 3) are shown figure 4. It is seen that $R$ vs $T$ dependence in the positions P2 (YBCO2-area) and P3 (YBCO2/LSMO-area) of the sample demonstrates nearly metallic behavior while the $R$ vs $T$ dependence for the position P1 (YBCO2/LSMO/YBCO1-area) is nonlinear. This means that properties of the YBCO film in the three-layer parts of the sample is worse in comparison with those in the single-, double- layer parts of the sample. In spite of this the resistive SC transition starts at $T \approx 90$ K and is over at $T \approx 84$ K in all the areas of the sample. The temperature of the start of SC transition, measured by AC response method, is close to the temperature of the end of resistive SC transition. It can be seen (figure 5) that the local areas A2 and A4 of the sample containing the single- or double layers (YBCO2, YBCO2/LSMO, YBCO2/YBCO1) are characterized with a steeper SC transition in the temperature scale in comparison with the areas A1, A3, which include the three-layer (YBCO2/LSMO/YBCO1) fragment of the sample. This result is in agreement with the results of the resistance measurements and shows a lower quality of YBCO film in the three-layer part of the sample which is due to the features of the technology. In spite of this, it can be concluded that the above technology allows growing of three-layer structures with $T_c \approx 84$ K.
Figure 4. Temperature dependences of the resistance measured by four probe method for the positions of the probes P1 (YBCO2/LSMO/YBCO1), P2 (YBCO2) and P3 (YBCO2/LSMO) (curves 1-3, respectively).

Figure 5. Temperature dependence of AC response signal of the different areas of a three-layer sample. Curves 1-4 are obtained for the areas of the sample marked by circles A1-A4 (see Figure 1), respectively.

4. Conclusions
DC and RF magnetron sputtering techniques were used for growing nano-films of HTS YBCO and ferromagnetic (FM) manganite LSMO materials onto LAO and ALO substrates and for preparing of single-, double- and three-layer structures in different areas of the same substrates. The procedure allowed growing of structures on LAO substrates where the critical temperature of YBCO thin film components was more than 84 K. LSMO films grown ALO substrates were ferromagnetic. The YBCO films grown on such LSMO/ALO structures did not demonstrate superconductivity and led to a dramatic modification of the temperature dependence of the resistance.

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