Finite size effects on magnetic flux penetration into YBCO/LSMO hybrids

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Abstract. The attractive idea to create artificial superconductor/ferromagnet heterostructures (SC/FM) for easy control of the superconductor properties by magnetic field is widely considered last decade. Of a special interest for applications are the HTSC/FM heterostructures, particularly the YBCO/LSMO, where the magnetization value of LSMO could be adjusted by doping, by variation of oxygen content, and magnetic domain structure could be controlled by reasonable magnetic field. We concentrate on the in-plane field penetration into the YBCO/LSMO hybrid film, which is of practical interest as the in-plane field easier saturates the magnetic film. The study is performed by the magneto-optic visualization technique at T down to 7 K. We found a striking transformation of the in-plane external field into a wave of alternating perpendicular flux, the particular features of which depended on the temperature and magnetic prehistory at temperature above superconducting transition. To shed light on the mechanism of the effect, we have investigated the magnetic domain pattern of manganite film and its transformations due to variation of temperature and the field. The results are discussed taking into account the finite size of the hybrid structure and the magnetostatic field distribution.

1. Introduction

The development of spintronics devises requires the production of new type of materials with high response to weak impact and with low noise. For these purpose new artificial materials are creating based on dilute materials or on heterostructures of super-thin films. Particular interesting are heterostructures of superconductor/ferromagnet films (S/F), in which superconducting properties are supposed to be easily controlled by weak magnetic field [1]. Despite the controvert nature of superconductivity and magnetism, they can coexist in heterostructures and bring new phenomena and new material properties, such as pi-junctions [2], localized domain-wall superconductivity [3], the spin-valve effect [4], spin-orientation-dependent superconductivity [5] and so on. The more appealing look S/F heterostructures with high temperature superconductors (HTSC) as they give the possibility to operate at temperature over the liquid helium. It is found that lattice parameter of high temperature superconductor YBCO matches well to that of LCMO and LSMO, so that epitaxial YBCO films grow on manganites by laser or RF magnetron deposition, but the properties of both films are found to become worth than that of single films (both ferromagnetic and superconductor transition temperature [6], critical current of superconductor in heterostructures YBCO/LCMO, YBCO/LSMO are found to become reduced [7]). Nevertheless such structures of HTSC/manganites as well as conventional S/F
heterostructures are considered as prospective for applications and the properties of such materials are now widely studied experimentally and theoretically.

This paper is devoted to a study of some special features of penetration of longitudinal magnetic field into YBCO/manganites heterostructure. Such geometry is interesting because it corresponds to easy magnetization of magnetic layer, which results from two factors, the minimum of demagnetization factor at magnetization along the film plane, and the coincidence of one of easy axes of manganite with film plane. So, any switching effects, like magnetoresistance or spin-valve, would appear at smaller fields. Besides, the in-plane magnetic field is mainly produced by the current, which flow along the superconducting film before current induced field starts to penetrate the superconductor, and this field could effectively affect the magnetic state of ferromagnetic layer in heterostructure. Using a technique of visualization of magnetic flux distribution [8] we have found the principal alteration of the pattern of flux penetration into YBCO film due to the vicinity of ferromagnetic film and qualitative variation of magnetization kinetics of magnetic layer due to the vicinity of superconductor comparing with those of single films.

2. Experimental

The experiments were performed on La$_{0.7}$Sr$_{0.3}$MnO$_3$/YBa$_2$Cu$_3$O$_{7-d}$ heterostructures. Ferromagnetic La$_{0.7}$Sr$_{0.3}$MnO$_3$ (LSMO) thin films were grown in-situ on (100) LaAlO$_3$ (LAO) substrates by RF off-axis magnetron sputtering technique. DC off-axis double magnetron sputtering was used for deposition of YBCO films on the top of the LSMO layer. The deposition conditions were nearly same as given in our previous papers [9]: the substrate temperature $T_{dep}$ and the film annealing temperature $T_A$ were $T_{dep} \approx 700 \, ^\circ C$, $T_A \approx 600 \, ^\circ C$, respectively, for preparing manganite films and the film deposition was carried out at the substrate temperature $T_{dep} \approx 780 \, ^\circ C$ and the annealing temperature was $T_A \approx 530 \, ^\circ C$ for YBCO films. The thickness of the superconducting YBCO and ferromagnetic LSMO layers in the samples was $d_1 \approx 40 \, \text{nm}$ and $d_2 \approx 20 \, \text{nm}$, respectively. The temperature of superconducting transition $T_c$ was about 88 K.

The observation of the pattern of magnetic flux penetration was performed by magneto-optic visualization technique (MO) by means of magneto-optically active indicator film placed on a flat surface of the studied object [8]. Because of the continuity of perpendicular component of induction at transition from one to another media, the out-of-plane component of induction is the same in the studied object and in the thin indicator film. Therefore local rotation of polarization of the light in the indicator corresponds to the induction distribution in the sample; and the map of reflected light intensity obtained in polarized light microscope at a few degrees uncrossed polarizes, corresponds to the induction distribution. Using this method one can find both the value of perpendicular induction component and the direction of the induction. Gray contrast on images corresponds to zero induction, bright and dark one corresponds to two opposite polarities of the induction; the more is the difference in the contrast between medium gray and bright (or dark) the higher is local induction. The MO visualization in the geometry of in-plane magnetizing field and perpendicular observation was successfully used before to reconstruct the domain structure of bulk manganites [10], to reveal phase separation in manganites [11], to visualize the correlation between mesoscopic inhomogeneities of bulk superconductor and the critical current [12]. This geometry is often used to study the magnetization process of magnetic materials [13]. The same geometry is used in this study: magnetic field is applied along the plane of the sample; the observation of the induction distribution is done on the sample plane. Therefore homogeneous field penetration into the sample would not produce any contrast, any inhomogeneity as well as appearance of perpendicular to the sample plane component of the induction will cause the appearance of the contrast.

3. Experimental results

3.1. Magnetic domain structure of manganite film

The magnetic domain structure of virgin heterostructure film was found to be microdomains with out-of-plane magnetization, Fig.1a, everywhere in the sample plane but near the twin boundaries [14].
where distinctly seen narrow stripes with perpendicular magnetization were localized, which is in agreement with observations in ref. [15, 16]. This twin system in our samples was seen already at room temperature at observation of sample surface in scattered light. The position of these twins was reproduced after thermocycling up to 400 K and down to 20 K. So, we conclude that this twins are caused by twins in LAO substrate.

The microdomains with out-of-plane magnetization were replaced by macro-domains with an in-plane magnetization under the action of saturated in-plane or out-of-plane magnetic field. The formed due the magnetization domain structure remained unchanged after the field switching off. Posterior remagnetization while the field reverse occurred via the motion of 180-degree domain walls, Figs. 1b-1e [14].

Depending on the temperature, the width of the domain wall and its "texture" were varied from narrow wall of zigzag like type, Fig.1b, into diffuse domain wall, Fig.1e. Nevertheless, the wall remained of Bloch type, i.e. the magnetization vector across the wall rotated through the out-of-plane directions. These walls were nucleated at the film edges when the external field exceeded some threshold value $H_c$. Then, with an increase of external field, the walls moved to the film interior. The value of $H_c$ was temperature dependent. $H_c$ varied from a few of Oersted to hundreds of Oersted with temperature decrease from 300 K down to 20 K. For virgin and residual magnetic domain structure, $H_c$ differed at least twice.

So, the magnetic domain structure of manganite film is found to be strongly dependent on the prehistory. Therefore to have reproducible results we use the same procedure of orientation of magnetization into the film plane by the in-plane magnetic field before every low-temperature experiment.

Figure 1. a – virgin magnetic domain structure in twin free LSMO area; b-e – 180-degree domain wall between wide domains with in-plane magnetization in the same area, $T = 311, 200, 150$ and 95 K. The width of every image is 140 microns. Black arrows show direction of spontaneous magnetization in domains.

3.2. Magnetization of hybrid film at $T < T_c$
Remagnetization kinetics of hybrid YBCO/LSMO film at $T < T_c$, differs principally from those at $T > T_c$. First consider the flux penetration pattern at $T \approx 85$ K, i.e. a few below $T_c$. After application of in-plane magnetic field, the magnetization direction at sample edge becomes inverse, which corresponds to the nucleation of a domain wall at the edge, Fig.2a. Then, instead of moving of narrow domain wall from sample edge, the band with the flux of the same polarity as was concentrated on the sample edge begins the widening and an inverse flux appears near the edge. This band broads to the sample interior with field growth, Fig. 2b, and after getting the maximum flux density, the band gets detached from the sample edge. Between this band and sample edge inverse flux enters the sample, compare Figs. 2b and 2d. So, the magnetization of hybrid film by the in-plane magnetic field causes the penetration of alternative perpendicular flux into heterostructure. The process is illustrated in Figs. 2a-2c by MO images of flux distribution and by profiles of perpendicular component of induction, which are taken perpendicular to sample edge along the field direction. One can see, that perpendicular magnetization disturbance appears on macroscopic distance, $dx \sim 300 \mu m$, which is thousands larger than the thickness of both magnetic and superconducting layers, $d = d_1 + d_2 = 60$ nm. The described pattern of the flux penetration is valid only in the vicinity of $T$ to $T_c$. The pattern becomes more complicated with temperature reduction, Figs. 3a-3c.
The same as before, the perpendicular component of the induction $B_z(x)$ becomes generated under the in-plane field near the YBCO film edge. Differently from previous situation, the inverse induction appears simultaneously in the sample interior, not at the sample edge, where it remains slightly over zero. The flux front is not flat, but looks like finger-prints or set of spots, Figs. 3a,b. Such, let say, carrying positive flux spots fill up the whole sample area with in-plane field increase. Negative flux remains at that between "positive" spots. So, magnetization of the hybrid film by in-plane field at low temperature lead to disturbed wave of perpendicular induction, Fig. 3c. Note, that the perpendicular magnetic flux enters the same film area smoothly under the perpendicular magnetic field, Fig. 3d.

4. Discussion and conclusions

So, we have found, that an in-plane magnetic field applied to SC/FM hybrid film excites alternating perpendicular induction, which means that perpendicular or bent vortices enter very thin superconductor film under an in-plane field. The strength of induced perpendicular component of induction is compatible with the strength of the applied field. The width of the disturbed area is about 300 µm, which means it thousands times excides the thickness of both FM and SC films. At $T \sim T_c$ this disturbed zone is a couple of wide flux/antiflux bands, which spreads to the sample interior with field increase and decays moving away from the film edge. At $T < T_c$ the disturbed zone becomes the band of spot-like flux immerged into antiflux media. At that, the inhomogeneity of $B_z$ pattern is not
connected with the defects in magnetic or superconducting films because the domain walls moving under the in-plane field as well as the perpendicular flux entering the superconductor under perpendicular field do not experience such inhomogeneity.

To explain the results, we have studied the magnetic domain structure of manganite film and have found that there are two metastable states for magnetization of manganite film and two types of metastable domains. The virgin domain structure with perpendicular vector of spontaneous magnetic moment is supposed to be formed under the action of small perpendicular anisotropy, which arises from interface-related stresses, like it was found and discussed in ref.[17]. The residual state after magnetization by an in-plane field, that is the state with in-plane orientation of spontaneous magnetization, is the consequence of size (shape) effects. The shape anisotropy favors the in-plane orientation of magnetization. So, we have found that there are at least two close by energy domain states. The magnetization reversal of manganite film occurs via the nucleation and motion of 180-degree head-to-head domain walls with out-of-plane magnetization. The width of the area, covered by the wall increases up to 100 µm with temperature decrease. This feature of domain wall structure transformation is definitely connected with existence of two metastable domain structures in manganite film.

We suppose, that the screening of stray fields of domain wall by superconductor causes the widening of the domain wall. And vice versa, the stray fields of domain wall disturb the induction in the superconductor film and cause the appearance of perpendicular induction in the superconductor film, which moves with the domain wall in manganite.

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