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Temperature Dependence of Magnetization Reversal of Thin Manganite Film

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The magnetic domain structure, its transformation with temperature, and the magnetization reversal in 20 nm $La_{0.7}Sr_{0.3}MnO_3$ film grown on $LaAlO_3$ substrate by off-axis magnetron sputtering at 700 °C and post-annealed at 600 °C were studied in a wide temperature range. The magnetic domains with either in-plane- or out-of-plane-orientation of the vector of spontaneous magnetization were observed in the same film depending on the prehistory. The domains with the in-plane magnetization were found to be more stable. Magnetization reversal of the film was shown to occur via the nucleation and motion of 180-degree head-to-head domain walls, the number and the type of which were found to be dependent on temperature. Moreover, the transition between two magnetization reversal regimes was found at 30 K.

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1. Introduction

Thin manganite films as well as bulk manganites exhibit the important ability to vary the electrical resistance under external magnetic fields [1–6]. Magnitude of the effect, which could reach 1000%, makes manganites the prospective materials for applications. However, the colossal magnetoresistance (CMR) is observed under the magnetic field of a few tesla and in narrow temperature range close to the temperature of magnetic reordering. The resistance switching under the moderate magnetic field (MFMR) is observed mainly in thin film manganites. MFMR is less than 100%, i.e., lower than CMR, but it takes place in a wide temperature range, which looks attractive for practice. The effect is associated with electron scattering by small scale inhomogeneities like grain boundaries, twins, magnetization disturbance by strain-induced magnetic anisotropy, and spin-dependent scattering by magnetic domain boundaries [6, 7]. The domain structure is very sensitive to all mentioned above defects and could highlight not only the scale of magnetic ordering, but the defect distribution, too [8, 9]. However, despite a long study of manganites [10, 11], little is known about the magnetic domain structure of bulk and especially thin film manganites [12]. According to a few available publications concerning direct visualization of magnetic domains in films, domains with perpendicular spontaneous magnetization are observed in the films with thickness below 100 nm [13–15]. Domains with the in-plane magnetization are usual for the perfect films with thickness over 100 nm; the perpendicular magnetization occurs there in the vicinity of structural defects (twins, grain boundaries) only [16, 17]. Though, recent results on variation of pattern of magnetic field penetration into manganite/superconductor heterostructures at temperature below superconducting transition give evidence that magnetic domain structure of thin manganite film is determined not only by the growth conditions and film thickness, but by the magnetic field during magnetization reversal [18]. The last data motivate the present study of magnetic domain structure of thin manganite film and investigation of its transformation under the in-plane magnetic field and with the temperature.

2. Experimental

The experiments were performed on 20 nm $La_{0.7}Sr_{0.3}MnO_3$ film epitaxial grown on $LaAlO_3$ substrate by off-axis magnetron sputtering at 700 °C and post-annealed at 600 °C [19]. The main area of the films was twin free. High quality of the films was confirmed by good homogeneity of local magnetic properties, such as constancy of local coercivity for domain wall motion along the film and constancy of temperature of the transition into the ferromagnetic state, which was observed at $T_c = 340$ K.

The study of magnetic domain structure was performed by magnetooptic visualization technique (MO) in the temperature range of 6–340 K, like it was done in [18]. Bismuth doped $Y_3Fe_5O_{12}$ film with 20 grad/T/μm rotation of polarization of incident and reflected polarized light, was used as an "indicator" film of magnetic induction. To increase the sensitivity of the method, up to 16

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images were averaged frame by frame and background image was subtracted. So, we got the sensitivity to the field about 0.05 mT.

3. Magnetic domain structure and magnetization reversal

The magnetic domain structure of the film after zero field cooling from $T > T_c$ was hardly resolved by MO because of the domains were a little larger than 1 μm (Fig. 1a). Spontaneous magnetization vector $\boldsymbol{M}_s$ in domains had alternate perpendicular component, the exact direction of which was impossible to recognize. $\boldsymbol{M}_s$ changed its orientation to the sample plane through the growth of stripe domains with out-of-plane magnetization followed by $\boldsymbol{M}_s$ rotation to the plane under the in-plane magnetic field of about 26 mT [20]. The film remained in the single domain state with $\boldsymbol{M}_s$ oriented in the film plane after field switching off.

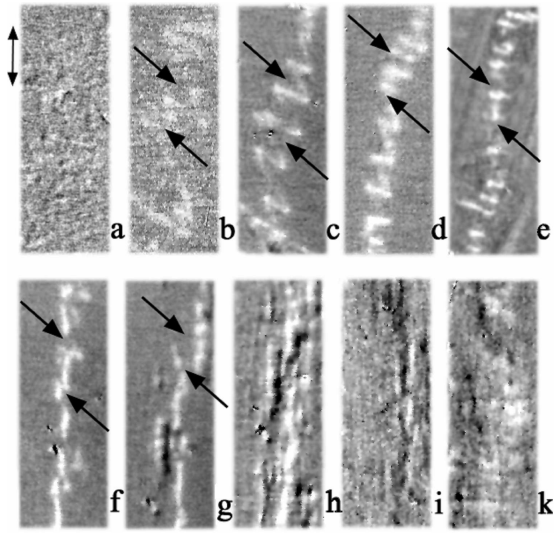

Fig. 1. (a) — small scale magnetic domain structure of the film at $T = 300$ K after zero-field cooling from $T > T_c$; (b–k) — 180-degree domain wall between domains with in-plane $\boldsymbol{M}_s$ (the direction is shown by black arrows) at: $T = 311$, 306, 300, 273, 200, 177, 154, 69, and 26 K. Black double arrow (left top corner) corresponds to 100 μm scale.

Magnetization reversal of the film at next field cycling occurs via the nucleation of the 180-degree head-to-head domain wall (DW) on the sample edges and propagation of the walls through the whole sample area (Figs. 1b–e). The nucleation of DW and its motion begin when the field strength exceeds some threshold value H_c, which depends upon the temperature. H_c increases thirty times with temperature decrease from 310 K down to 10 K (Fig. 2). The typical images of DWs are shown in Figs. 1b–k. One could see that all DWs are 180-degree head-to-head domain wall, but DWs look different depending upon the temperature. The walls are zigzag-like at $T > 200$ K. The lower the temperature, the shorter zigzag lines (compare Figs. 1b–e). In the temperature range of 200–60 K the zigzags disappear and the wall becomes straightened. At once multiple stroke lines appear before the moving domain wall. This is fair indication that the nucleation of domains with inverse magnetization occurs ahead of moving of the domain wall. These stroke lines become shorter and more numerous with the temperature decrease. Finally, at $T < 30$ K the domain wall spreads into a wide band of "boiling" magnetization with bubbles of opposite perpendicular magnetization alternating in the direction across the wall. The width of this band exceeds 100 μm.

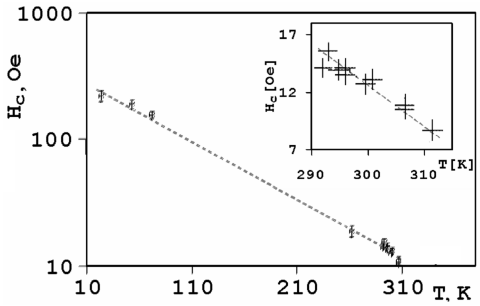

Fig. 2. Variation of the coercitivity of magnetic domain wall in manganite film with temperature, semilog plot. Inset — high temperature range, linear scales.

So, we observe the transition between two magnetization reversal modes; the first is the nucleation and motion of a few domain walls, and the second is the process of inhomogeneous rotation of magnetization from multiple nucleation centres. This transformation of magnetization reversal with temperature seems to be a specific feature of manganite films.

4. Discussion

Zigzag-like domain walls appear in thin ferromagnetic films as a result of competition between dipolar forces and magnetocrystalline anisotropy in thin films with head-on magnetization between nearest-neighbour domains [21]. These walls have been originally observed in thin film magnetic recording media, where head-on domains are induced by the application of a recording head field, and have been then reported in several magnetic materials, such as Gd–Co, Co, epitaxial Fe films [21–23], and many others. In our case the zigzag-like domain walls are observed in 340–200 K temperature range. It was natural to suppose that below 200 K nothing should happen with domain wall configuration, because exchange, dipolar and crystallographic anisotropy energies are weakly varied at low temperature. For example, zigzag-like domain walls in thin FeNi single-layer film have been observed in a wide temperature range from room temperature down to 10 K, and zigzag became even more pronounced with temperature decrease [24]. However, in manganite film zigzag domain walls are straightened with temperature decrease from 340 K down to 200 K.

Cerruti and Zapperi [25] have calculated the energetics of zigzag domain wall considering the magnetostatic anisotropy, and disorder contributions. They roughly estimated the dynamic coercivity H_c^{dyn} and the period of zigzag domain wall p as $H_c^{dyn} \sim K_u/\boldsymbol{M}_s$, and $p \sim \boldsymbol{M}_s^2/K_u$, where K_u is the anisotropy energy, $\boldsymbol{M}_s$ is the spontaneous magnetization value. Besides, they performed simulation of variation of H_c^{dyn} with temperature. A comparison of our experimental and estimated values of H_c^{dyn} and p at room temperature shows reasonable agreement. However, experimentally obtained $H_c(T)$ dependence demonstrates much deeper increase of H_c with temperature decrease than the calculated $H_c^{dyn}(T)$ even under the assumption that the rate of field increase of 20 T/s used in the experiments is slow.

What is the origin of the discrepancy? According to our observations, $\boldsymbol{M}_s$ in domains is in line with $\langle 110 \rangle$ directions, which are projections of easy $\langle 111 \rangle$ axes of bulk manganite. The in-plane $\boldsymbol{M}_s$ orientation is probably a consequence of the influence of demagnetization factor. On the other hand, the $La_{0.7}Sr_{0.3}MnO_3$ film is stressed due to 2% misfit with the $LaAlO_3$ substrate [26–28]. The stresses favour the perpendicular to the film $\boldsymbol{M}_s$ orientation, which plays probably the key role in the formation of virgin small-scale domains formed during the cooling from $T > T_c$ in zero external field (Fig. 1a). If we suggest that stress-induced anisotropy increases with temperature decrease, then we could explain the additional growth of H_c. Thus, we could explain the unexpected growth of H_c with temperature decrease; nevertheless, we could not find the origin of disappearance of zigzags on domain walls at $T < 200$ K.

The straightening of the wall (the simplification of domain wall appearance) is followed by the complication of magnetization process, namely, multiple nucleation of new domains ahead of the moving domain wall. The same was observed in FeNi/FeMn heterostructure, where the interface defects between ferromagnet and antiferromagnet layers start to contribute to magnetization reversal at low temperature, which produces complicated domain pattern and increase in H_c by the order of magnitude [24]. Note, in our case H_c is varied approximately in the same range of values, and H_c grows by tens times with temperature decrease down to 10 K, like in [24] (Fig. 2). Taking into account huge increase in the dynamic coercivity with temperature decrease and suggesting again the increase in perpendicular stress induced anisotropy, while K_u and $\boldsymbol{M}_s^2$ are nearly constant, we suggest that the energy of nucleation of new magnetic phase becomes compatible with the coercivity at $T \approx 150$ K. This results in the appearance of nucleation of new domains ahead of domain wall. The lower the temperature, the higher dynamic coercivity, and the more nucleation centres become active. The nucleation process becomes so active at T below 30 K that the domain wall spreads into the wide band of bubble domains. It may be considered as the inhomogeneous magnetization rotation in a wide band between two domains with in-plane magnetization.

5. Conclusions

Magnetic domain structure and magnetization reversal kinetics of thin manganite film are studied in the temperature range of 340–6 K. It is established that the magnetization reversal process is temperature dependent. At higher temperature the magnetization reversal occurs via the nucleation and motion of a few domain walls. Below 30 K the magnetization reversal proceeds through inhomogeneous magnetization rotation. An unusual transformation of a type of domain walls with temperature is found. Zigzag-like domain walls, which are typical for thin film with in-plane anisotropy, are observed only in the temperature range of 340–200 K, the straight domains walls are observed at 200–60 K, diffuse wide domain walls are found below 30 K. The dynamic coercivity of domain walls is found to be a nonlinear function of temperature, rising by tens times with temperature reduction down to 10 K.

The transition in magnetization reversal mechanism and in the type of domain walls from usual narrow domain wall to diffuse one, as well as the unexpected growth of dynamic coercivity with temperature reduction are explained qualitatively taking into account increasing stress-induced anisotropy. No explanation is found for the straightening of zigzag domain wall.

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References

[1] E.L. Nagaev, *Physics-Uspekhi* **39**, 781 (1996).

[2] J. Toepfer, J.B. Goodenough, *J. Solid State Chem.* **130**, 117 (1997).

[3] V.M. Loktev, Yu.G. Pogorelov, *Low Temp. Phys.* **26**, 171 (2000).

[4] E. Dagotto, T. Hotta, A. Moreo, *Phys. Rep.* **344**, 1 (2001).

[5] M.B. Salamon, M. Jaime, *Rev. Mod. Phys.* **73**, 583 (2001).

[6] P.K. Siwach, H.K. Singh, O.N. Srivastava, *J. Phys., Condens. Matter* **20**, 273201 (2008).

[7] H.S. Wang, Q. Li, *Appl. Phys. Lett.* **73**, 2360 (1998).

[8] A. Khapikov, L. Uspenskaya, I. Bdikin, Ya. Mukovskii, S. Karabashev, D. Shulyaev, A. Arsenov, *Appl. Phys. Lett.* **77**, 2376 (2000).

[9] N.A. Tulina, L.S. Uspenskaya, V.V. Sirotkin, Y.M. Mukovskii, D.A. Shulyatev, *Physica C* **444**, 19 (2006), `http://arxiv.org/abs/cond-mat/0605457` .

[10] G.H. Jonker, J.H. Van Santen, *Physica* **16**, 337 (1950).

[11] E.O. Wollan, W.S. Koeller, *Phys. Rev.* **100**, 545 (1955).

[12] G. Jung, M. Indenbom, V. Markovich, C.J. van der Beek, D. Mogilyansky, Ya.M. Mukovskii, *J. Phys., Condens. Matter* **16**, 5461 (2004).

[13] J. Dho, Y.N. Kim, Y.S. Hwang, J.C. Kim, N.H. Hur, *Appl. Phys. Lett.* **82**, 1434 (2003).

[14] J. Dho, N.H. Hur, *J. Magn. Magn. Mater.* **318**, 23 (2007).

[15] Y. Wu, Y. Suzukia, U. Rudiger, J.Yu, A.D. Kent, T.K. Nath, C.B. Eom, *Appl. Phys. Lett.* **75**, 2295 (1999).

[16] V.K. Vlasko-Vlasov, Y.K. Lin, D.J. Miller, U. Welp, G.W. Crabtree, V.I. Nikitenko, *Phys. Rev. Lett.* **84**, 2239 (2000).

[17] F. Laviano, L. Gozzelino, E. Mezzetti, P. Przyslupski, A. Tsarev, A. Wisniewski, *Appl. Phys. Lett.* **86**, 152501 (2005).

[18] L.S. Uspenskaya, T. Nurgaliev, B. Blagoev, T. Donchev, S. Miteva, *Bull. Rus. Acad. Sci.: Phys.* **72**, 540 (2008).

[19] T. Donchev, V. Tsaneva, Z.H. Barber, T. Nurgaliev, L. Gravier, J.Ph. Ansermet, I. Petrov, V. Petrova, *Vacuum* **76**, 261 (2004).

[20] L.S. Uspenskaya, I.V. Kurbatova, T. Nurgaliev, S. Miteva, *Bull. Rus. Acad. Sci.: Phys.* **73**, 1110 (2008); L.S. Uspenskaya, T. Nurgaliev, S. Miteva, *J. Phys. D* 42, 185006 (2009).

[21] M.J. Freiser, *IBM J. Res. Dev.* **23**, 330 (1979).

[22] D. Dressler, J. Judy, *IEEE Trans. Magn.* **10**, 674 (1974).

[23] W.Y. Lee, B.-Ch. Choi, Y.B. Xu, J.A.C. Bland, *Phys. Rev. B* **60**, 10216 (1999).

[24] L.S. Uspenskaya, S.V. Egorov, *J. Phys., Conf. Series* **150**, 042224 (2009).

[25] B. Cerruti, S. Zapperi, *Phys. Rev. B* **75**, 064416 (2007).

[26] A.M. Haghiri-Gosnet, *J. Phys. D, Appl. Phys.* **36**, R127 (2003).

[27] Y.-A. Soh, G. Aeppli, C.-Y. Kim, N.D. Mathur, M.G. Blamire, *J. Appl. Phys.* **93**, 8322 (2003).

[28] J. Dho, N.H. Hur, *J. Magn. Magn. Mater.* **318**, 23 (2007).