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# Ferromagnetic State of $LaMnO_3$ Interlayer in $La_{0.7}Sr_{0.3}MnO_3/LaMnO_3/SrRuO_3$ Heterostructures

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**Abstract.** Magnetic state of epitaxial heterostructures $La_{0.7}Sr_{0.3}MnO_3/LaMnO_3/SrRuO_3$ (LSMO/LMO/SRO) was studied by SQUID magnetometer, ferromagnetic resonance (FMR) and polarized neutron reflectometry (PNR) techniques. The fit of PNR and FMR data give us the magnetization of each layer, while the SQUID gives the total magnetization of our structures. The magnetic moment of the LMO layer has the magnetization $4\pi M_{LMO}$=4.2kGs (2.4 $\mu_B$/Mn) at T=140K according to our PNR data fitting.

## Introduction

Tunnel junctions consisting of two ferromagnetic electrodes separated by an insulating layer are interesting system for creation nonequilibrium spin polarized states, as well as for applications in nonvolatile magnetic memory [1]. Large tunnel magnetoresistance required for practical use of such structures occurs when a weak external magnetic field changes direction of the magnetization for either one or two ferromagnetic electrodes. It is shown theoretically in [2] that the replacement of insulating layer (MgO or $SrTiO_3$) to nondoped manganite $LaMnO_3$ in magnetic tunnel structures of oxide materials significantly increases the magnetoresistance due to better crystallographic and magnetic (no nonmagnetic layer at the border) matching between the layers in the heterostructure.

This paper presents the results of magnetic study of epitaxial heterostructures containing of two ferromagnetic epitaxial $La_{0.7}Sr_{0.3}MnO_3$ (Curie temperature $T_C$ = 364K [3]) and $SrRuO_3$ ($T_C$ = 163 K [4]) thin films (hereinafter LSMO and SRO, respectively) separated by a thin layer of undoped manganite $LaMnO_3$ (LMO).

## SQUID measurements

The epitaxial magnetic films (LMO, LSMO and SRO) were prepared by laser ablation at temperatures of 700-800 ºC in an oxygen atmosphere on the substrate (110) $NdGaO_3$ (NGO). Epitaxial growth of the heterostructures is confirmed by X-ray diffraction patterns and transmission electron microscope pictures [5]. Magnetic properties of heterostructures were measured by SQUID magnetometer Quantum Design MPMS SQUID VSM in the temperature range 4-300 K. The temperature dependences of the in-plane magnetic moment of the heterostructure M(T) were measured by heating of the sample after pre-cooling in the magnetic field (Fig. 1a). A large contribution to the total magnetic moment of the heterostructure gives a paramagnetism of NGO substrate. To substract the paramagnetic contribution from the substrate we used M(T) curve, measured at H = 3000 Oe, predominantly consisting of the signal from the substrate. Result of the substraction is presented in Fig. 1b. As it can be seen in Fig. 1b, M(T) increases with decreasing temperature in the temperature range 160K < T < 300K, due to the increasing magnetization of

LSMO layer (LSMO $T_C$ > 300K). Further, at temperatures below 160K, an increase of the magnetic moment was caused by the transition of SRO layer to the ferromagnetic state. At temperatures below 100 K, a decrease of magnetization was observed, which is absent in our heterostructures without LMO layer.

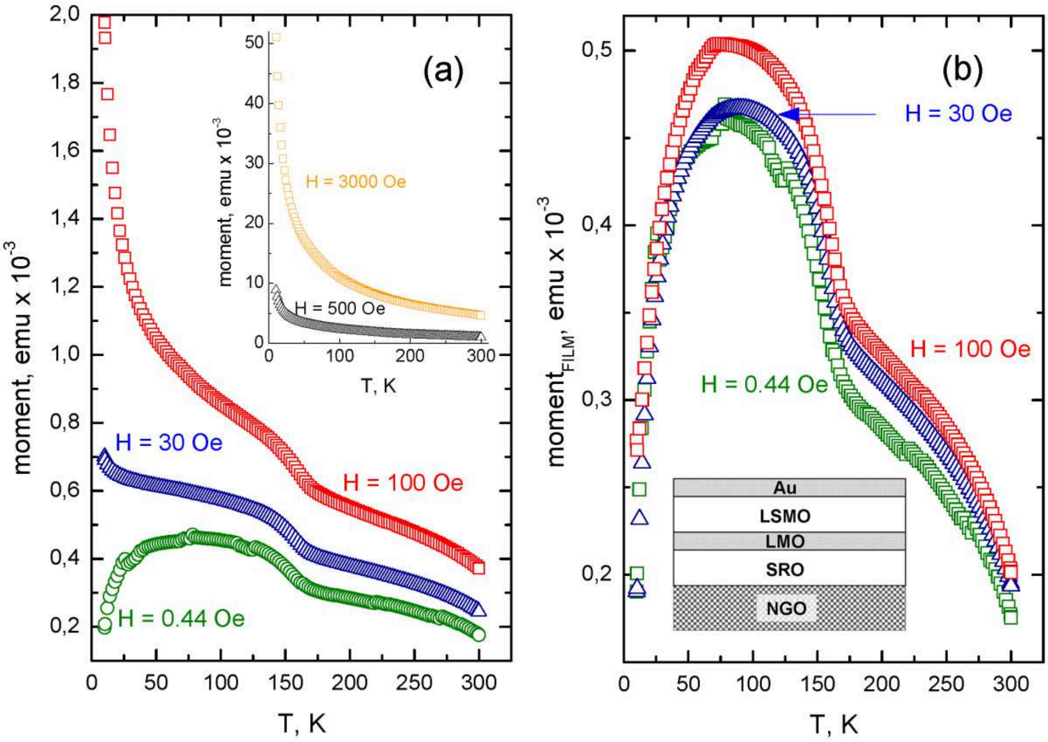


Fig.1. (a) The temperature dependence of the in-plane magnetic moment M(T) after cooling in the magnetic field, oriented parallel to the substrate surface. The heterostructure LSMO/LMO/SRO grown on a substrate (110) NGO. The thickness of LMO $d_{LMO}$ = 13nm. The thicknesses of other layers were around 40 nm. Inset shows M(T) at high magnetic field. (b) The magnetic moment of the heterostructure after subtraction of the paramagnetic contribution of NGO substrate. The layer structure of heterostructure is shown on inset.

**Polarized Neutron Reflectometry**

The SQUID data were supplemented with the data of Polarized Neutron Reflectometry [6]. Experiment was performed on the angle dispersive reflectometer NREX of the research reactor FRM II (Munich, Germany). The neutron reflectivity curves were measured using neutron beam with the wavelength λ=4.3 A in the range of the grazing incidence angles θ from 0.1° to 1°. For the quantitative analysis of the magnetic state of the system so called spin asymmetry of neutron scattering $SA(Q) = (R^+(Q) - R^-(Q))/(R^+(Q) + R^-(Q))$ were used. Here $R^+$ ($R^-$) is the reflectivity of neutrons with spin up (down), $Q=4\pi\sin\theta/\lambda$ is the momentum transfer in scattering process. The spin asymmetry is easily shown to be proportional to the Fourier transform of the depth profile of the magnetization of a structure. As it can be seen in Fig. 2, spin asymmetries measured at 140K and 200K have different shape and amplitude. The averaged spin asymmetry depicted in the inset to Fig. 2 shows that transition takes place below 200K. By the fitting of the experimental curves to model we can say that spin asymmetry at 200K can be described by magnetic moment of 2.7 $\mu_B$/Mn. Change of the spin asymmetry below 200K is explained by appearance of the magnetic moment in LMO layer. Far below the transition magnetic moment of LMO is calculated as 2.4 $\mu_B$/Mn.

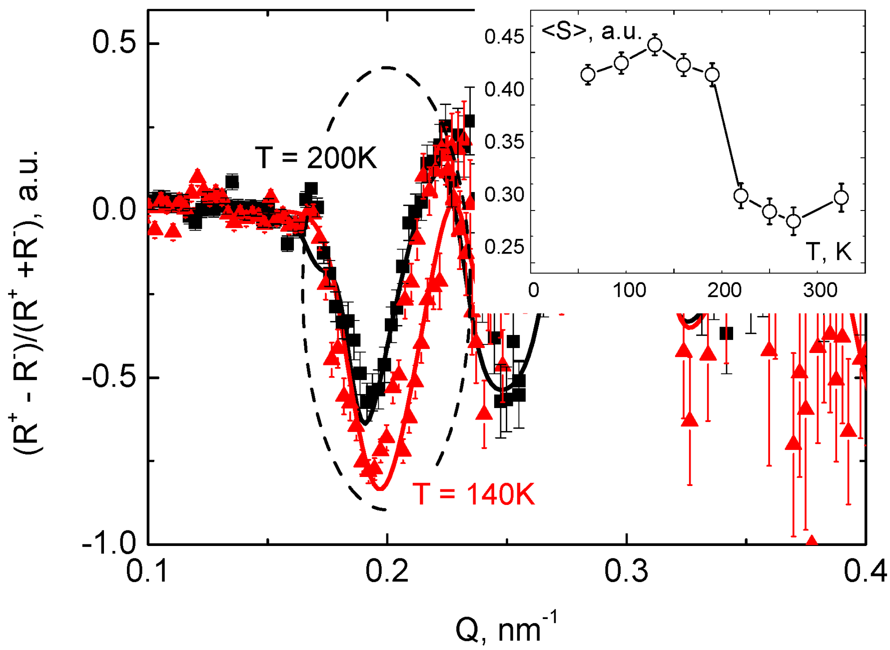


Fig. 2. Experimental (dots) and model (lines) spin asymmetries of neutron reflection for heterostructure with 13nm layer of LMO. Experimental curves were measured at 200K (squares) and 140K (triangles) in magnetic field of 30 Oe applied parallel to the sample surface. The inset presents the module of temperature dependence of spin asymmetry.

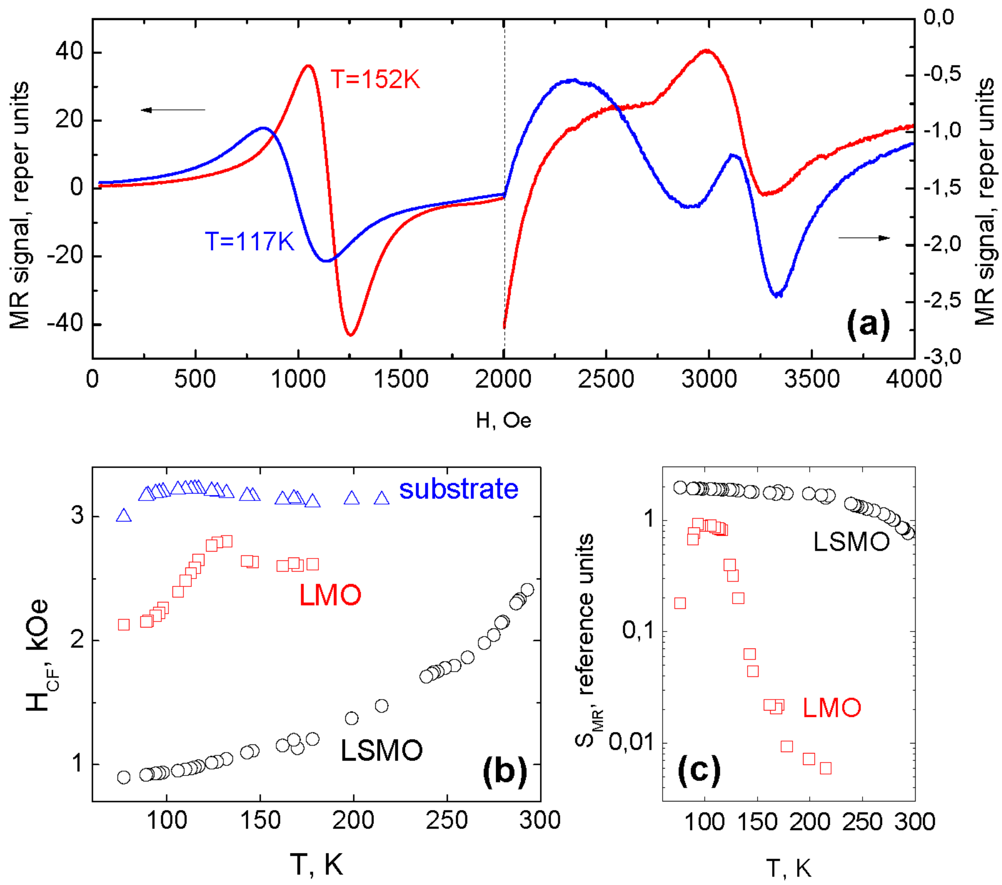


Fig. 3. (a) The magnetic resonance spectrum: the line for LSMO film at low H (around 1000 Oe) and LMO film + NGO substrate at higher H (around 3000 Oe) were shown for two T. (b) The temperature dependence of the central magnetic field of the ferromagnetic resonance for the following layers: LMO (squares), LSMO (circles) and substrate NGO (triangles). (c) The area of the resonance lines for LSMO and LMO films.

### Ferromagnetic resonance data

Magnetic resonance spectra of the heterostructures were investigated by Brucker spectrometer in the temperature range 77-300K. The external magnetic field and the magnetic component of the microwave field were lying in the plane of the substrate [3]. FMR line of LSMO layer was observed in the range 1000-2500 Oe (see Fig.3b). The shifts of line to low field with decreasing temperature, and increasing of the area under the absorption curve (see Fig. 3b,c) indicate on monotonically increasing of LSMO layer magnetization. At temperatures lower than 220 K there is a second line whose intensity increased 250 times when the temperature decreases to 100 K (see Fig. 3c). At $T < 130$ K the line begins to move to the low field, indicating that the ferromagnetic transition with $T_C \approx 130$ K arises. However, a further decrease in temperature leads to a sharp drop in intensity, possibly indicating the antiferromagnetic ordering at $T < 90$ K (see Fig. 3c).

### Summary

The SQUID magnetometer, neutron measurements and ferromagnetic resonance spectra at different temperatures were used to study the magnetic states of particular layers in the heterostructures LSMO/LMO/SRO deposited on the substrate (110) NGO. Ferromagnetic moment of LMO interlayer was detected in the plane of the substrate at temperatures below the Curie temperature of SRO film ($T_{C\ SRO} \sim 160$K).

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