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Magnetic and transport properties of $La_{0.8}Sr_{0.2}MnO_3/La_{0.8}Ca_{0.2}MnO_3$ bilayer

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Abstract

The effects of lattice strain on the magnetic and the transport properties of $La_{0.8}Sr_{0.2}MnO_3$ films grown on a $LaAlO_3$ (001) substrate and on a $La_{0.8}Ca_{0.2}MnO_3$ layer have been studied. It was observed that the metal-insulator and the ferromagnetic transitions turn out to be at higher temperatures for the film deposited on $La_{0.8}Ca_{0.2}MnO_3$ layer with respect to that on $LaAlO_3$. The dependence of Curie temperature on the bulk and the Jahn-Teller strains has also been determined.

Keywords : CMR materials, Bilayer structure, Magnetic properties, Transport properties

1. Introduction

The magneto-transport properties of hole-doped colossal-magnetoresistive (CMR) manganite perovskites exhibit a strong correlation with the lattice structure [1]. This phenomenon becomes apparent in thin films. A lattice strain (and stress), accumulated owing to the epitaxial growth of a film, plays an important role for formation of the spin and the charge-ordered states, the metal-insulator transition temperature, and the value of magnetoresistance [2-4].

The influence of the kind of single-crystalline substrates on the magnetic and the electronic properties of manganite films has been quite investigated [5-6]. On the other hand, the development of hybrid devices based on multilayered CMR films needs detailed information on the mutual influence between constituent layers. It is expected that the magnetic and the transport properties of the multilayer structure can substantially differ from those for the individual films of the constituent layers. In this paper, we report the experimental results for $La_{0.8}Sr_{0.2}MnO_3$ (LSM) and $La_{0.8}Ca_{0.2}MnO_3$ (LCM) films, and for a $La_{0.8}Sr_{0.2}MnO_3/La_{0.8}Ca_{0.2}MnO_3$ bilayer (BL).

2. Experiment

All the films were prepared by rf magnetron sputtering using the so-called "soft" (or powder) target [7]. The total pressure in chamber was 5×10^{-2} Torr with a gas mixture of Ar and O_2 (3 : 1). The substrate was a $LaAlO_3$ (001) single crystal (LAO) with an out-of-plane lattice parameter $c \cong 0.379$ nm for the pseudocubic symmetry. The substrate temperature during deposition was 750℃. Both LSM and LCM films were deposited with a thickness $d \cong 60$ nm, and the BL with the similar thickness for each layer and with LSM at the top. The θ-2θ x-ray diffraction (XRD) patterns were obtained using a Rigaku diffractometer with Cu K_α radiation. The lattice parameters evaluated directly from the XRD data were plotted against $\cos^2\theta/\sin\theta$. With

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an extrapolated straight line to $\cos^2\theta/\sin\theta=0$, a more precise determination of the lattice parameter was obtained. The resistance measurements were carried out by using the four-probe method in a temperature range of 4.2 - 300 K and a magnetic field up to 5 T. The magnetization in a field up to 100 Oe and the susceptibility at 500 Hz were taken with a Quantum Design SQUID magnetometer in a temperature range of 4.2 - 300 K.

3. Results and Discussion

Figure 1(a) presents the θ-2θ XRD scans for LSM (1), LCM (2) and BL (3) films. High intensities of the (00*l*) peaks manifests that the deposition results in highly c-oriented films. Figure 1(b) shows that the location of (002) Bragg peak for the BL is almost coincident with that for the LCM film. On the contrary, the peak of LSM film is distinctly shifted to a smaller angle. Therefore, the analysis of XRD data reveals that the out-of-plane lattice parameter for LSM film is strongly dependent on the substrate: $c \cong 0.398$ nm on the LAO substrate and $c \cong 0.391$ nm on the

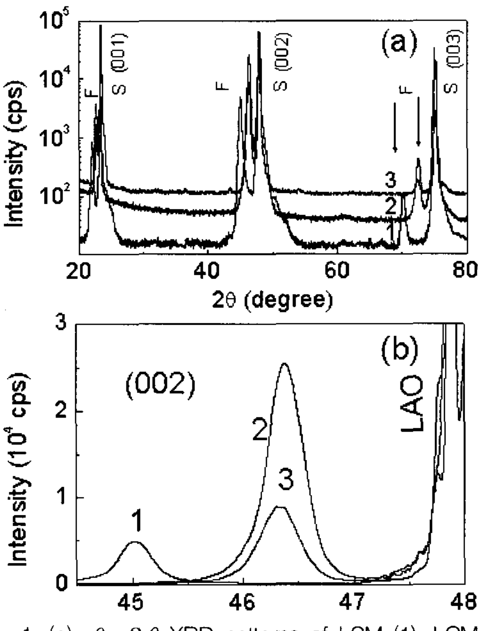

Fig. 1. (a) $\theta-2\theta$ XRD patterns of LSM (1), LCM (2) and BL (3) films. (b) The (002) XRD peaks.

$La_{0.8}Ca_{0.2}MnO_3$ film which has a lattice parameter $c \cong 0.3905$ nm.

Figure 2(a) displays the temperature dependence of resistance, $R(T)$, for the LSM, the LCM and the BL films without (solid circles) and with (open circles) an applied magnetic field of 5 T. The magnetic field was directed at right angle to both the film surface and the transport current. The experimental curves testify that the temperatures of metal-insulator (MI) transition for both LSM and LCM films are very similar to be about 230 K. The BL film undergoes the MI transition at 280 K that is higher than those for the individual

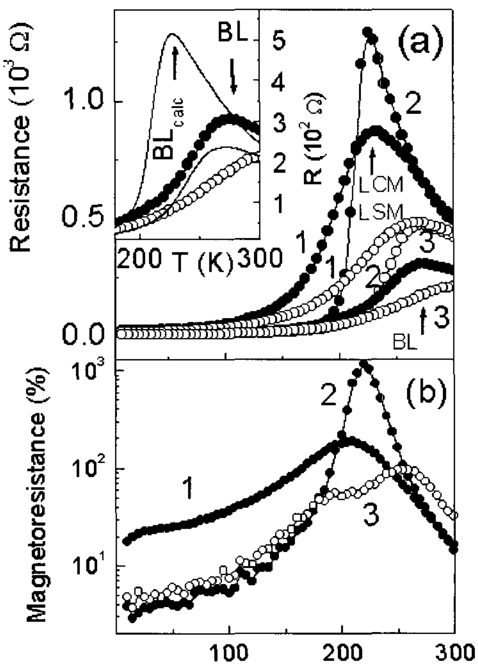

Fig. 2. (a) Temperature dependence of the resistance for LSM (1), LCM (2) and BL (3) films without (closed circles) and with (open circles) an applied magnetic field of 5 T. Lines are guides to the eyes. Inset displays the experimental (circles) and calculated (solid line) $R(T)$ dependences for the BL film. Arrows show the temperatures of MI transition for different samples. (b) Temperature dependence of the magnetoresistance for LSM (1), LCM (2) and BL (3) films. Lines are guides to the eyes.

films. The temperatures of MI transition for all the samples are indicated by arrows. The inset of Fig. 2(a) displays that the $R(T)$ behavior of BL film differs from that predicted by the simple two parallel-resistor model (solid line), where the first resistor corresponds to the LSM film (curve 1) and the second one to the LCM film (curve 2). Taking into account that the lattice parameter c is changed significantly only for the LSM film deposited on the LCM layer, it is reasonable to suggest that the increase in the MI transition temperature for BL is provided by improved magnetic and electronic properties of LSM film only.

Figure 2(b) presents the temperature-dependent magnetoresistance, $MR(\%) = [R(0)-R(H)]\ 100/R(H)$, obtained for LSM (1), LCM (2) and BL (3) films in an applied magnetic field of 5 T. Here, $R(0)$ and $R(H)$ are the resistances without and with magnetic field. It is seen that a slight enhancement in MR for BL, with respect to the individual LSM and LCM films, is observed only at high temperatures. In the low-temperature range the MR value of BL remains smaller than that of the LSM film and mimics the MR(T) behavior for the LCM film.

Figure 3(a) shows both field-cooled (FC) and zero-field-cooled (ZFC) temperature-dependent magnetization curves for the LSM, the LCM and the BL films. Arrows point out the corresponding Curie temperatures. The LCM film manifests a sharp transition to the ferromagnetic state at $T_C = 230$ K that is coincident with the published results for the as-grown films [3]. On the contrary, the LSM film displays a broad and smooth magnetic transition near $T_C \cong 260$ K. Moreover, the absolute value of the saturated FC magnetization is a half of that for the LCM film of similar thickness. The same behavior of the $M(T)$ and a lower value of T_C with respect to the bulk have been observed early for a $La_{0.67}Sr_{0.33}MnO_3$ film deposited on a LAO substrate [8,9]. It was explained by the 3-dimensional strain states in the film, governed by the epitaxial mode of the film growth. The temperature-dependent magnetization for BL is significantly different from the predicted

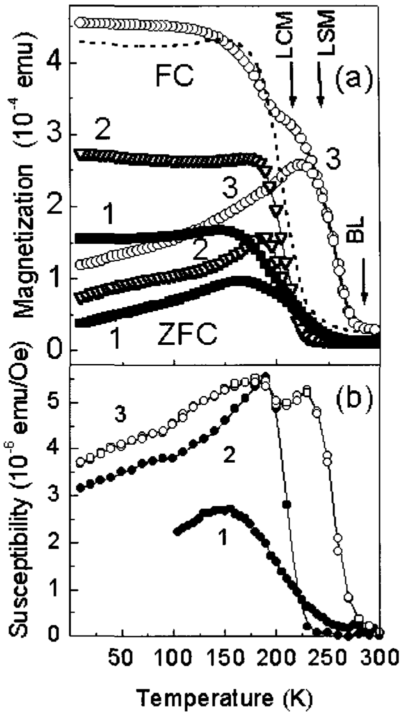

Fig. 3. (a) Temperature dependence of the FC and the ZFC magnetization for LSM (1), LCM (2) and BL (3) films. Lines are guides to the eyes. Arrows indicate the temperatures of magnetic transition for different samples. Dashed line was obtained by a simple addition of FC $M(T)$ curves (1) and (2). (b) Temperature dependence of the susceptibility for LSM (1), LCM (2) and BL (3) films. Lines are guides to the eyes.

one by a simple addition of the $M(T)$ values for both individual LSM and LCM films. The dashed line in Fig. 3(a) presents the predicted curve: $M_{BL}(T) = M_{LCM}(T) + M_{LSM}(T)$, where $M_{LCM}(T)$ and $M_{LSM}(T)$ are the magnetizations for the LCM and the LSM films, respectively. Since the thicknesses of the individual films are similar to those of the corresponding layers in the BL, the added curve turns out to be fairly coincident with the experimental one at low temperatures (in a range of the saturation magnetization). However, the ferromagnetic transition of BL film takes place at a higher temperature ($T_C \cong 280$ K) than the predicted one. The obtained result confirms the significant change in the magnetic properties of the LSM film deposited on LCM with respect to that on LAO.

This conclusion is supported by the temperature dependences of susceptibility for LSM (1), LCM (2) and BL (3) films in Fig. 3(b). Taking into account that the low-temperature peak of the susceptibility for BL (curve 3) mimics that for the individual LCM film, one can deduce that the second peak is relevant to the LSM layer in the BL. It is seen that the magnetic transition of the LSM film deposited on LCM becomes sharper and the saturated magnetization is achieved at a higher temperature than those of the bare LSM film (see curve 1).

Let us consider the possible mechanisms of the enhanced magnetic and transport properties of the LSM film on LCM with respect to that on LAO. The aforementioned analysis of x-ray data showed that the out-of-plane lattice parameter c is larger for LSM. It is well known that the LSM thin films grown on LAO substrates exhibit an out-of-plane uniaxial tensile strain and, correspondingly, an in-plane biaxial compressive one [9,10]. Assuming that the film is strained from the ideal bulk structure and that the structure is a single perovskite, the in-plane lattice parameter of film can be estimated from the unit cell volume of the bulk. The bulk $La_{0.8}Sr_{0.2}MnO_3$ compound has a rhombohedral pseudocubic symmetry ($R\bar{3}_c$) with hexagonal lattice parameters of $a_h \cong 0.5517$ nm and $c_h \cong 1.3359$ nm [11]. There are equivalent to cubic lattice parameters of $a \cong b \cong c \cong 0.3871$ nm, and to a unit cell volume $V \cong 0.058$ nm^3. Therefore, the in-plane lattice parameter for our LSM on LAO comes to be $\sqrt{V/c} \cong a \cong 0.3828$ nm which is almost identical to the value obtained for an epitaxial $La_{0.67}Sr_{0.33}MnO_3$ thin film [1]. For our LSM on LCM, the in-plane lattice parameter becomes larger and is equal to $a \cong 0.3852$ nm. This difference between film and bulk lattice parameters leads to for mation of the mentioned in-plane biaxial compressive strain, $\varepsilon_{100} = (a_{\text{film}} - a_{\text{bulk}})/a_{\text{bulk}}$ and out-of-plane uniaxial tensile strain, $\varepsilon_{100} = (c_{\text{film}} - c_{\text{bulk}})/c_{\text{bulk}}$. The performed calculations show that, for the LSM on LAO, $\varepsilon_{100} \cong -1.37$ % and $\varepsilon_{001} \cong 2.8$ % while -0.49 % and 1.0 %, respectively, for the LSM on LCM. For weaker strains and a cubic symmetry the Curie point can be expressed, according to Millis model, by [12]

$$T_C(\varepsilon) = T_C(\varepsilon=0)\left(1 - \alpha\varepsilon_B - \frac{1}{2}\Delta\varepsilon_{JT}\right)$$

where $\varepsilon_B = (2\varepsilon_{100} + \varepsilon_{001})$ is the bulk strain, $\varepsilon_{JT} = \sqrt{2/3}(\varepsilon_{001} - \varepsilon_{100})$ is the Jahn-Teller strain, $\alpha = (1/T_C)(dT_C/d\varepsilon_B)$, and $\Delta = (1/T_C)(d^2T_C/d\varepsilon_{JT}^2)$. For the last two quantities, we are taking the values in Ref. [12], i.e., $\alpha = 10$ and $\Delta = 1000$. Using this equation and the obtained ε_{100} and ε_{001} values for our LSM film and layer, we calculated the change in Curie temperature: $T^{calc}_{C_{LSM/LCM}} / T^{calc}_{C_{LSM/LAO}} \cong 1.07$, which is an excellent agreement with our experimental result, $T_{C_{LSM/LCM}} / T_{C_{LSM/LAO}} \cong 1.077$. The Curie temperature for an unstrained LSM film was estimated to be $T_C(\varepsilon=0) \cong$ 285 K which, according to the magnetic phase diagram of the bulk compound, corresponds to a composition of $x = 0.18$ [13]. The observed difference in T_C between the bulk and the film is explained by a slight oxygen deficiency, $\delta \cong 0.01$, which is typical for an as-deposited film without additional oxygenated annealing. Therefore, a strong correlation between the crystal-lattice distortion, and the electronic and the magnetic states is confirmed in the CMR materials.

4. Conclusions

We have investigated the magnetic and the transport properties of $La_{0.8}Sr_{0.2}MnO_3$ films grown on a $LaAlO_3$ (001) substrate and on a $La_{0.8}Ca_{0.2}MnO_3$ layer. Based on the analyses of the θ-2θ XRD and $M(T)$ data, it is concluded that there is a strong correlation between the crystal-lattice distortion, and the electronic and the magnetic states. We also confirmed significant changes in the magnetic properties of the LSM film deposited on LCM with respect to that on LAO.

Acknowledgments

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