Magnetocrystalline anisotropy and spin-wave stiffness in tensile-strained $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ films: An investigation via ferromagnetic resonance

DUANMU QingYong¹, TONG Wei², YANG Lei¹, HAO Lin¹, ZHANG ZhongFeng¹,
WANG XiaoPing¹ & ZHU Hong^{1*}

¹ Department of Physics, University of Science and Technology of China, Hefei 230026, China;

² High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, China

Received April 10, 2013; accepted June 5, 2013; published online July 24, 2013

Tensile-strained epitaxial $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ (LBMO) film has been prepared by magnetron sputtering technique on (001) oriented spinel MgAl_2O_4 substrate. The transport and magnetic measurements give an insulator-metal transition and paramagnetic-ferromagnetic transition occurring at ~ 150 K and 250 K respectively, which implies the phase separation in such a tensile-strained film. By analyzing the angular and temperature dependences of the ferromagnetic resonance (FMR), we determine the magnetocrystalline anisotropy of the film. It is found that the tensile-strained film is dominated by an easy-axis corresponding to the compressive out-of-plane direction, though the magnitudes of anisotropy constants are relatively small and their temperature dependences are some complex. Furthermore, the FMR spectra show additional spin wave resonance (SWR), and the field positions can be indexed to follow a linear dependence on the square of index n . The scaling gives a spin-wave exchange stiffness D of $20.7 \text{ meV } \text{\AA}^2$ at low temperature, which is less than half of that in strain-free LBMO films, implying that the double exchange interaction is remarkably suppressed in the tensile-strained LBMO films.

tensile strain, magnetotransport, FMR, magnetocrystalline anisotropy, spin wave resonance

Citation: Duanmu Q Y, Tong W, Yang L, et al. Magnetocrystalline anisotropy and spin-wave stiffness in tensile-strained $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ films: An investigation via ferromagnetic resonance. *Chin Sci Bull*, 2013, 58: 4057–4063, doi: 10.1007/s11434-013-6012-y

Alkaline earth-doped manganites ($\text{La}_{1-x}\text{A}_x\text{MnO}_3$, $\text{A}=\text{Sr}, \text{Ca}, \text{Ba}$) are particularly interesting as constituents in heterostructures because of sharing the same basic perovskite crystal structure with many dielectrics, high- T_c superconductors, and ferroelectrics. Therefore, applications of the colossal magnetoresistance (CMR) [1,2] of doped manganites would likely involve magnetic heterostructures [3,4]. One can see novel properties in the study of epitaxial manganite films on various substrates, which is potential for device applications. Several groups [5] have shown that the properties such as Curie temperature T_c , magnetocrystalline anisotropy (MCA), and magnetoresistance effect are extremely sensitive to chemical pressure due to alkaline-earth substitution for the rare-earth ions as well as hydrostatic

pressure [6]. Therefore, it is not surprising that the internal “press” consequent upon lattice mismatch between film and substrate would dramatically affect the magnetic properties of doped manganite thin films. The importance of strain on MCA has been established both experimentally [4–6] and theoretically [7], and it is found that the anisotropy in films is significantly different from that in bulk due to epitaxial strain [8,9] and film thickness [9]. MCA plays an important role in many magnetic applications including recording media [10] and magnetoresistive sensors [11], because it affects various behaviors such as magnetization curve, domain structure and coercivity. Therefore, appropriate choice of substrates or buffer layers for epitaxial films is an effective strategy to tune their functionality.

In our early work [12], using ferromagnetic resonance (FMR) method, the MCA of the compressively-strained

*Corresponding author (email: zhuh@ustc.edu.cn)

$\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ (LBMO) films grown on LaAlO_3 (LAO) substrate was studied. An anomalous easy-plane MCA has been found in such compressively-strained LBMO films, which is in contrast to the out-of-plane easy-axis in the same strained $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ /LAO films [9]. Naturally, we could conjecture that the easy axis would turn from the in-plane direction to out-of-plane direction, corresponding to a strain changes from compressive to tensile in the LBMO films, just contrary to the uniaxial easy-plane MCA in tensile-strained $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ films predicted by Shick's calculation [7]. The unit cell of the LBMO is pseudocubic with lattice constant $a = 3.909 \text{ \AA}$. To achieve tensile strain in LBMO films, selecting a suitable substrate is the key point. While both cubic rock-salt MgO ($a = 4.21 \text{ \AA}$) and cubic spinel MgAl_2O_4 (MAO) with $a = 8.08 \text{ \AA}$ may be candidates, the lattice mismatch η between LBMO film and MgO substrate is about 7.7%, which is too large to epitaxially grow LBMO thin film on MgO substrate [13,14]. However, the η between LBMO film and MAO substrate is only about 3.35%, which is less than half of that in LBMO/MgO. Ying et al. [15] have successfully grown the perovskite Sr-doped BaTiO_3 films on MAO substrates by PLD, so we select MAO as substrate to epitaxially grow tensile-strained LBMO films.

In this paper, we report the static magnetic, transport properties and the FMR study of tensile-strained optimally hole-doped $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ thin film epitaxially grown on (001) MAO substrate. A notable difference of $\sim 100 \text{ K}$ between the metallic- and ferromagnetic-transition is presented in the tensile-strained LBMO/MAO film, which can be attributed to the phase separation picture. The magneto-crystalline anisotropy of the LBMO/MAO film is investigated using angle-dependent FMR to verify the above conjecture. Although the anisotropy constants are much smaller than those of LBMO/LAO by one order of magnitude and exhibit a complex evolution over temperature, the out-of-plane easy-axis anisotropy is presented in the temperature range of 40–150 K for the tensile-strained LBMO/MAO film as expected. Besides that, several well-resolved modes of spin wave resonance (SWR) are also observed in a wide temperature range in the configuration of magnetic field perpendicular to the film plane. After fitting the FMR spectra to the Lorentzian derivative function, we index several modes of SWR. The SWR fields follow the quadratic dependence on mode numbers as proposed by Kittel [16], which provides a straightforward way to determine the spin-wave stiffness D . It is found out that the spin-wave stiffness constant is less than that of the strain-free $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ /SrTiO₃ film [17], which means that the ferromagnetic double exchange is suppressed in biaxial tensile-strained LBMO film due to the elongation of Mn-O-Mn bond lengths.

1 Experiments

The $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ films were prepared by dc magnetron

sputtering technique on (001) orientated MgAl_2O_4 substrates. The procedure to synthesize $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$ target used during sputtering was given elsewhere [18], and the LBMO films were grown on the substrates at 700°C in a mixed Ar/O₂ background pressure of 5 Pa for 30 min. After the deposition, the films were cooled down to room temperature at a rate of $10^\circ\text{C}/\text{min}$ in pure oxygen atmosphere at 15 Pa. To achieve high epitaxial quality and eliminate oxygen deficiency, the as-grown films were subsequently annealed in O₂ ambient in 1 atm gas flow at 550°C for 50 h. The cross-sectional SEM imaging indicated a flat film surface and thickness of about 67 nm. The room-temperature X-ray diffraction (θ - 2θ scan and φ scan) showed the epitaxial (001) orientation and 4-fold symmetry of LBMO films with an out-of-plane lattice parameter $c = 3.89 \text{ \AA}$, which is less than that of the bulk LBMO ($a = 3.91 \text{ \AA}$) and confirmed the biaxial tensile strain imposed by the substrate ($a/2 = 4.04 \text{ \AA}$). Detailed study of structural properties of the film will be reported in forthcoming papers.

The temperature-dependent magnetization (M - T) of the LBMO/MAO film was measured using a commercial superconducting quantum interference device (SQUID) (Quantum Design MPMS XL-7) magnetometry in the temperature range between 5 and 350 K after field-cooling (FC). The measurements of isothermal magnetization for H applied parallel and perpendicular to the film plane were also performed at different temperatures. The dc resistivity ρ was measured using standard four-probe technique at zero magnetic field and keeping an external field H applied in the film plane, respectively.

The FMR measurements were carried out at fixed microwave frequency of 9.39 GHz using a Bruker EMX plus 10/12 electron paramagnetic resonance (PMR) spectrometer equipped with an Oxford liquid helium continuous flow cryostat and a cylindrical cavity. The actual data consisting of derivative profiles of the absorbed power were obtained by a standard field-swept technique with ac field modulation and lock-in detection. The schematic diagrams of the FMR experimental setup and measurement techniques were given in [12]. At various temperatures, the angular dependence of FMR measurement was done in two geometry configurations, i.e. the polar angle $\theta = 0^\circ$ (field perpendicular-to-plane, PTP) configuration and $\theta = \pi/2$ (field in-plane, IP) configuration. By investigating the dependence of the resonance field H_r on temperature in the PTP configuration, we studied the uniaxial anisotropy and its temperature dependence. In the IP configuration, by changing the azimuth angle φ continuously and remaining $\theta = \pi/2$ unchanged, the in-plane anisotropy of the LBMO/MAO film was investigated.

2 Results and discussion

2.1 Magnetotransport and static magnetic properties

Figure 1 displays the temperature dependences of electrical

Figure 1 (a) Temperature dependence of resistivity for the LBMO/MAO film under different external field H . (b) Temperature dependence of magnetization after field cooling; the applied field is 100 Oe parallel to the film plane.

resistivity and magnetization for the LBMO/MAO film. With decreasing temperature at zero magnetic field, as shown in Figure 1(a), the electrical resistivity increases as insulator till 150 K, then changes into a metallic behavior, and finally presents an upturn at temperatures below 50 K. While the metal-insulator transition (MIT) is one of the common features of doped manganites, the transition temperature $T_{MIT} \sim 150$ K is sizeable lower than 345 K measured in LBMO bulk sample, which can be attributed to the effect of tensile strain in the LBMO/MAO film. One unexpected point is that the electrical resistivity increases once again at lower temperatures, which might be related to the spin-glass state in the film [19,20]. With increasing H from 0 to 30 kOe, the electrical resistivity decreases visibly and the MIT point moves gradually to higher temperatures just as previously observed in manganite films.

Figure 1(b) shows the temperature-dependent magnetization $M(T)$ with magnetic field $H=100$ Oe applied in the film plane after field cooling (FC) mode. The M - T curve indicates a ferromagnetic-paramagnetic transition at the Curie temperature $T_c \sim 250$ K, much lower than that of strain-free LBMO/STO ($T_c \sim 320$ K), which can be attributed to the weakening of the double exchange interaction due to the tensile strain in LBMO film [18]. It is noteworthy that the Curie temperature is obviously higher than the MIT temperature in the LBMO/MAO film. Such a divergence between the two transition temperatures can be considered in the framework of phase separation and percolation transport scenario [21]. Another point is that the ferromagnetic transition in the LBMO/MAO film is wider than that in the LBMO/STO film, which reflects a gradual relaxation of strain from interface to surface in such a strained film. The

measurement of isothermal magnetization at 5 K (not shown here) for H applied parallel to the film plane gives a saturation magnetization M_s of $3.45 \mu_B/\text{f.u.}$, which is close to the theoretical value $3.7 \mu_B/\text{f.u.}$

2.2 Main mode and magnetocrystalline anisotropy analysis

Figure 2 shows the FMR fields of the LBMO/MAO film in two configurations, PTP and IP. It should be pointed out that additional SWR are observed in PTP configuration, and will be analyzed in detail in Section 2.3. Therefore the FMR field shown here for PTP configuration is that of the main mode ($n=0$) resonance. As one can see, at low temperature, the FMR position is strongly shifted to high field above PMR position when H is applied perpendicular to the LBMO film plane, while it is below PMR position when H is in the film plane. With increasing temperatures, the FMR fields converge gradually toward the PMR field before T_c is approached. In PTP configuration, demagnetization effect or shape anisotropy may account for the great shift of FMR field to PMR position. But besides that, MCA can play its role in FMR, especially in such a strained film. Considering the biaxial strained film as a crystal structure with tetragonal symmetry, the free-energy density F in an applied dc magnetic field H can be written as [22]

$$F = -\mu_0 \vec{M} \cdot \vec{H} + \frac{1}{2} \mu_0 M^2 \cos^2 \theta + K_2 \sin^2 \theta + K_4^\perp \sin^4 \theta + K_4^\parallel \sin^4 \theta \cos 4\varphi, \quad (1)$$

where the first term describes the Zeeman energy; the second term is the demagnetization energy denoting shape anisotropy; the last three terms represent the MCA energy of a tetragonal structure, where K_2 is the second-order anisotropy constant and $K_4^\perp$, $K_4^\parallel$ are the fourth-order anisotropy

Figure 2 Temperature dependences of the FMR fields for the LBMO/MAO film observed in two different configurations: IP (open circles) and PTP (open squares). In PTP configuration, the data shown here is the field of the main mode of SWR. Solid lines are guides for the eye. The PMR position is marked by dashed line at $H=3350$ Oe. Inset: the schematic diagrams of the FMR experimental setup.

constants perpendicular and parallel to the film plane, θ and φ are described in the inset of Figure 2.

A brief theory on MCA constants and a detailed description about the analysis of FMR experimental data can be found in [12,22]. Therefore in the PTP configuration, according to [12], one can get

$$\frac{\omega}{\gamma} = H_r + \frac{2K_2}{\mu_0 M_s} - M, \quad (2)$$

where ω is the circular frequency of microwave, $\gamma = g\mu_B\hbar^{-1}$ is the gyromagnetic ratio and $-M$ is the demagnetization field depending on temperature.

While in IP configuration, we have

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H_r + M - \frac{1}{\mu_0 M_s} (2K_2 + 4K_4^\perp + 4K_4^\parallel \cos 4\varphi) \right] \times \left[H_r - \frac{16}{\mu_0 M_s} K_4^\parallel \cos 4\varphi \right]. \quad (3)$$

By substituting the PTP data in Figure 2 into eq. (2), we can get the anisotropy constant K_2 at various temperatures. Figure 3 shows the temperature dependences of anisotropy constants for the LBMO/MAO film. Clearly, the maximum value of K_2 is $2 \times 10^4 \text{ J/m}^3$ at low temperature, which is approximately equal to the absolute value of K_2 of tensile-strained $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3/\text{STO}$ [8] film ($\eta=1.16\%$) with easy-plane character. K_2 here is about one order of magnitude smaller than the absolute value of K_2 for the compressively-strained LBMO/LAO film [12] and $\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3/\text{STO/Si}$ film [23] with less tensile strain ($\eta \sim 0.51\%$), which implies in some ways that the tensile strain suppresses the uniaxial MCA in manganite films. Besides that, the sign of K_2 changes from positive to negative with increasing temperature above $\sim 150 \text{ K}$. This nonmonotonic behavior was also observed in LBMO/LAO films by Lofland et al. [24], according to whom the nonmonotonic behavior is the result

Figure 3 Magnetocrystalline anisotropy constant K_2 (open squares) and $K_4^\perp$ (open circles) as functions of temperature for the LBMO/MAO film. Solid lines are guides for the eye.

of magnetostriction. As we know, positive K_2 signifies a uniaxial anisotropy with the easy axis perpendicular to the film plane, while negative K_2 corresponds to an easy-plane anisotropy. Therefore LBMO/MAO film exhibits an easy-plane character at $150 \text{ K} < T < T_c$, but has an uniaxial anisotropy (easy axis) at $T < 150 \text{ K}$, which is consistent with the conjecture that compressive/tensile strain in LBMO films results in easy-plane/easy-axis MCA. Referring to the transport properties mentioned above, we can find out that the sign reversion of K_2 just occurs at MIT temperature, i.e. $\sim 150 \text{ K}$, which suggests a hidden correlation between the MCA and transport property in the tensile-strained LBMO/MAO film. Reminiscing to the phase separation picture, the ferromagnetic-metallic (FM) clusters sprout from the paramagnetic-insulating (PI) matrix at temperatures below $T_c \sim 250 \text{ K}$, but they are too small to connect with each other, so the sample displays a ferromagnetic insulator behavior. Meanwhile, the lattice strain in the small FM clusters can be relaxed through the surrounding PI matrix, and then the film shows a small negative K_2 . With decreasing temperature, the FM clusters grow gradually. At $T = T_{\text{MIT}} \sim 150 \text{ K}$, the FM clusters are big enough to connect with each other, i.e. the system reaches the percolation threshold, and thus the transport behavior is dominated by the metallic network. At the same time, the LBMO film displays an expected positive K_2 induced by the tensile strain because the relaxation of strain is difficult in the big and crowded FM clusters.

To obtain the fourth-order anisotropy constants, we investigated the azimuth angle φ dependence of resonance field for the LBMO/MAO film. The sample actually shows a very weak four-fold in-plane anisotropy. With varying the azimuth angle φ and remaining the polar angle $\theta = \pi/2$ unchanged, the oscillation amplitude of the resonance field is only about 10 Oe , corresponding to a negligible in-plane anisotropy constant $K_4^\parallel \sim 20 \text{ J/m}^3$ (not shown in Figure 3). By substituting the calculated K_2 and the in-plane data (shown in Figure 2) into eq. (3) and neglecting $K_4^\parallel$, we get the fourth-order anisotropy constant $K_4^\perp$ at various temperatures as shown in Figure 3. With decreasing temperature to $\sim 80 \text{ K}$, one can see that the value of $K_4^\perp$ is almost zero, implying a negligible fourth-order anisotropy. With further decreasing temperature below $\sim 60 \text{ K}$, $K_4^\perp$ becomes negative and decreases rapidly to $-6 \times 10^4 \text{ J/m}^3$ at $\sim 2 \text{ K}$, and its absolute value is comparable with $K_4^\perp$ of the $\text{La}_{0.7}\text{Sr}_{0.7}\text{MnO}_3/\text{STO/Si}$ films [23]. Comparing with the previously reported LBMO/LAO film [12], which shows nearly unchanged $K_4^\perp$ and monotonic decreasing resistivity till low temperature, it seems that such a sharp decrease of $K_4^\perp$ in the LBMO/MAO film is related to the upturn of resistivity at temperatures below $\sim 50 \text{ K}$, but further work is still necessary to understand it in more detail.

According to the MCA energy expressed in eq. (1) with

$K_4^{\parallel} \approx 0$, the MCA effective field can be written as

$$H_K^{[001]} = \frac{2K_2}{\mu_0 M_s} \quad \text{and} \quad H_K^{[100]} = -2 \cdot \frac{K_2 + 2K_4^{\perp}}{\mu_0 M_s} \quad \text{for out-of-}$$

plane and in-plane directions, respectively. So from $T_c \sim 250$ K to $T_{MIT} \sim 150$ K, the LBMO/MAO film displays an easy-plane anisotropy with $H_K^{[100]} \sim 100$ Oe; for $40 \text{ K} < T < 150$ K, it shows a uniaxial anisotropy with easy-axis along [001] direction and $H_K^{[001]} \sim 550$ Oe. Finally, because the absolute value of $K_4^{\perp}$ exceeds K_2 at $T < 40$ K, the MCA energy reaches its minimums at both $\theta = 0^\circ$ and $\theta = \pi/2$, indicating that the film displays two easy directions parallel and perpendicular to the film plane, respectively. As a whole impression, the tensile-strained LBMO/MAO film presents a weak magnetocrystalline anisotropy, but the out-of-plane anisotropy is evident compared with the compressively-strained LBMO/LAO film.

2.3 FMR spectra and spin wave mode analysis

Figure 4 shows the observed typical spectrum at 9.39 GHz and 180 K in PTP configuration. A series of additional peaks are discerned clearly, leading to the suggestion of the appearance of SWR. The SWR in manganites was firstly observed by Lofland et al. [17] in LBMO thin films. For the films allowing the excitation of the standing SWR, the SWR must be taken into account in eq. (2). According to Kittel [16], and considering the magnon dispersion law $E = Dk^2$, eq. (2) can be rewritten as

$$\frac{\omega}{\gamma} = H_r + \frac{2K_2}{\mu_0 M_s} - M + \frac{Dk^2}{\hbar\gamma}. \quad (4)$$

If surface spins are completely pinned or completely unpinned, then spin wave vector can be written as $k = n^2 \pi^2 / L$, where L is the film thickness, and n corresponds to the number of half wavelength across the film thickness for the

Figure 4 FMR and spin wave resonance spectrum at 9.39 GHz and 180 K. The solid line shows a fit based on a Lorentzian derivative absorption function. The inset region is shown on an expanded-vertical scale.

SWR modes. Therefore one can get

$$\frac{\omega}{\gamma} = H_r + \frac{2K_2}{\mu_0 M_s} - M + \frac{Dn^2 \pi^2}{\hbar\gamma L^2}. \quad (5)$$

Equation (5) gives a series of resonance fields H_m (written as H_n hereafter) corresponding to different integer n , i.e. additional modes of SWR character as shown in Figure 4. The strongest peak in Figure 4 is assigned to $n=0$ corresponding to the uniform FMR mode [25], and the solid line shows a fit based on a Lorentzian derivative function to precisely determine the resonance fields. For a Lorentzian derivative function, the peak-to-peak width $\Gamma = W/\sqrt{3}$, where W is the full width at half maximum (FWHM). For example, the H_r and Γ of the main mode at $T=180$ K are determined as 7128 Oe and 52 Oe, respectively.

After that, the SWR field positions are indexed to give a good match to a linear dependence of H_n on n^2 as shown in Figure 5. We assign consecutive numbers to mode index n and check whether the linear dependence of H_n on n^2 holds as predicted by eq. (5). The best correspondence to eq. (5) is achieved for the sequence $n=0, 5, 7, 9, \dots$, and the odd numbers of n implied that the spins at surface in our film are completely pinned. The absence of the lower-mode peaks was also observed in permalloy film by Seavey and Tannenwald [26], who attributed it to the strong damping of the lower resonance modes.

As depicted in Figure 5, the slopes of H_n vs n^2 lines become abrupt at $T \leq 40$ K, yielding stronger spin-wave exchange stiffness. Figure 6 shows the exchange stiffness

Figure 5 Plot of mode field H_n vs n^2 at different temperatures. Symbols indicate H_n measured at fixed microwave frequency 9.39 GHz and microwave power of 2 mW. The solid lines show the linear fit to the data. For clarity and comparison, the data for $T \leq 40$ K are shown in panel (a), which is on the same scale as panel (b).

Figure 6 Temperature dependence of the spin-wave stiffness. Symbols indicate the result calculated from the slope of H_n vs n^2 in Figure 5. The solid line is the fitting curve by eq. (6), where $D(0)=16.36 \text{ meV Å}^2$, and $\beta=4.8 \times 10^{-7} \text{ K}^{-5/2}$.

constants D deduced from the slopes of H_n vs n^2 lines according to eq. (5) at various temperatures. It can be seen in Figure 6 that $D=20.7 \text{ meV Å}^2$ at $T=2 \text{ K}$, which is only about half of 47 meV Å^2 for strain-free LBMO/SrTiO₃ films [17]. The reduction of stiffness constants may arise from the suppression of magnetic coupling due to the tensile strain. Spin-wave theory [27] suggests that the dynamical interaction between the spin waves gives a $T^{5/2}$ behavior:

$$D(T)=D(0)(1-\beta T^{5/2}), \quad (6)$$

where $\beta \propto \bar{l}^2$, and $\bar{l}$ gives the range of the exchange interaction. The solid line in Figure 6 is the fitting of eq. (6) to the experimental data with $\beta=4.8 \times 10^{-7} \text{ K}^{-5/2}$, a reasonable value compared with $\beta=2.9 \times 10^{-7} \text{ K}^{-5/2}$ for strain-free LBMO/SrTiO₃ films [17]. The fitting curve is in quite good agreement with measured D except for $T \leq 40 \text{ K}$, below which the electrical resistivity shows an upturn, suggesting some relationship between magnetic exchange and delocalization of e_g electrons. According to eq. (6), the abrupt increase of D corresponds to the suppression of the range of exchange interaction $\bar{l}^2$, suggesting the enhanced localization of itinerant electrons, i.e. the increase of resistivity in the framework of double exchange, which is confirmed by the ρ vs. T curves at low temperatures shown in Figure 1.

3 Conclusions

The tensile-strained La_{0.67}Ba_{0.33}MnO₃ films grown on (100) MAO substrates have been achieved by dc magnetron sputtering technique. We have measured the static magnetic, transport properties and taken the FMR study of the LBMO/MAO films. The results indicate that the tensile strain in the LBMO/MAO film strongly suppresses the double exchange interaction, which in turn leads to the decrease of the Curie temperature T_c and phase separation characteristic, i.e. the MIT temperature $T_{MIT} \sim 150 \text{ K}$ is much lower than $T_c \sim 250 \text{ K}$.

Meanwhile, the tensile strain also weakens the MCA obviously by one order of magnitude, compared with that of compressively-strained LBMO/LAO films [12], and then the MCA displays a subtle relationship with the transport properties. The LBMO/MAO film exhibits a weak in-plane anisotropy at temperature between T_c and T_{MI} . With further decreasing temperature, it clearly shows a uniaxial anisotropy with easy-axis along the out-of-plane direction till $T \sim 40 \text{ K}$, below which the resistivity changes into insulator state again, and then the film displays two easy directions parallel and perpendicular to the film plane, respectively. On the whole, the out-of-plane easy-axis anisotropy in the LBMO/MAO film is consistent with the prediction proposed in our previous work [12], i.e. compressive/tensile strain in LBMO films results in easy-plane/easy-axis MCA, which is totally opposite to what happens in Sr- and Ca-doped manganite films [9]. Besides that, the spin wave resonance has also been observed in a wide temperature range in the configuration with H perpendicular to the film plane. By scaling the SWR modes at various temperatures, the temperature dependence of the spin-wave stiffness constant D is obtained following the work of Lofland et al. [17]. It is found out that $D(0)$, which is proportional to the strength of exchange interaction, in the tensile-strained LBMO film is half of that in the strain-free films [17]. The result demonstrates again that the magnetic coupling is weakened by tensile strain in the LBMO/MAO film due to the elongation of the Mn-O bond lengths. The results on MCA are important to tailor the magnetization curves and other magnetic properties in heterostructures to realize their functionality.

We would like to thank Dr. Li Pi for valuable discussion and technical help during the experiment. This work was supported by the National Natural Science Foundation of China (1174261).

- 1 Vonhelmolt R, Wecker J, Holzapfel B, et al. Giant negative magnetoresistance in perovskitelike La_{2/3}Ba_{1/3}MnO_x ferromagnetic-films. *Phys Rev Lett*, 1993, 71: 2331–2333
- 2 Jin S, Tiefel T H, McCormack M, et al. Thousandfold change in resistivity in magnetoresistive La-Ca-Mn-O films. *Science*, 1994, 264: 413–415
- 3 Steenbeck K, Eick T, Kirsch K, et al. Influence of a 36.8 degrees grain boundary on the magnetoresistance of La_{0.8}Sr_{0.2}MnO_{3-delta} single crystal films. *Appl Phys Lett*, 1997, 71: 968–970
- 4 Jun Z, Tanaka H, Kanki T, et al. Strain effect and the phase diagram of La_{1-x}Ba_xMnO₃ thin films. *Phys Rev B*, 2001, 64: 184404
- 5 Kwon C, Robson M C, Kim K C, et al. Stress-induced effects in epitaxial La_{0.7}Sr_{0.3}MnO₃ films. *J Magn Magn Mater*, 1997, 172: 229–236
- 6 Hwang H Y, Palstra T T M, Cheong S W, et al. Pressure effects on the magnetoresistance in doped manganese perovskites. *Phys Rev B*, 1995, 52: 15046–15049
- 7 Shick A B. First-principles calculation of uniaxial magnetic anisotropy and magnetostriction in strained colossal magnetoresistance films. *Phys Rev B*, 1999, 60: 6254–6257
- 8 O'Donnell J, Rzechowski M S, Eckstein J N, et al. Magnetoelastic coupling and magnetic anisotropy in La_{0.67}Ca_{0.33}MnO₃ films. *Appl Phys Lett*, 1998, 72: 1775–1777

- 9 Xiong C M, Sun J R, Shen B G. Dependence of magnetic anisotropy of the $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ films on substrate and film thickness. *Solid State Commun*, 2005, 134: 465–469
- 10 Carcia P F, Meinhaldt A D, Suna A. Perpendicular magnetic anisotropy in Pd/Co thin film layered structures. *Appl Phys Lett*, 1985, 47: 178–180
- 11 Han D H, Zhu J G, Judy J H, et al. Effect of stress on exchange coupling field, coercivity, and uniaxial anisotropy field of NiFe/NiO bilayer thin films. *Appl Phys Lett*, 1997, 70: 664–666
- 12 Jin Z, Wei T, Li B, et al. Easy-plane magnetocrystalline anisotropy of compressive strained (La,Ba) MnO_3 film. *J Appl Phys*, 2012, 112: 013913
- 13 Orgiani P, Adamo C, Barone C, et al. Epitaxial growth of $\text{La}_{0.7}\text{Ba}_{0.3}\text{MnO}_3$ thin films on MgO substrates: Structural, magnetic, and transport properties. *J Appl Phys*, 2008, 103: 093902
- 14 Hayashi K, Ohta E, Wada H. Effect of substrate--film lattice mismatch in $\text{La}_{0.7}\text{Ba}_{0.3}\text{MnO}_{3-\delta}$ thin films for transport properties. *J Vac Sci Tech A: Vac Surf Films*, 2001, 19: 2905–2909
- 15 Ying Z, Zhou X Y, Yun P, et al. Comparison of structures and properties of BST thin films grown on LAO and MAO substrates. *Integr Ferroelectr*, 2006, 86: 103–108
- 16 Kittel C. Excitation of spin waves in a ferromagnet by a uniform RF field. *Phys Rev*, 1958, 110: 1295–1297
- 17 Lofland S E, Bhagat S M, Kwon C, et al. Standing spin wave resonances in manganite films. *Phys Lett A*, 1995, 209: 246–248
- 18 Li B, Yang L, Tian J Z, et al. Influence of compressive strain on oxygen distribution in $\text{La}_{0.7}\text{Ba}_{0.3}\text{MnO}_3$ thin films. *J Appl Phys*, 2011, 109: 073922
- 19 Yang S Y, Kuang W L, Liou Y, et al. Growth and characterization of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ films on various substrates. *J Magn Magn Mater*, 2004, 268: 326–331
- 20 Mathieu R, Svedlindh P, Nordblad P. Re-entrant spin glass transition in $\text{La}_{0.96-y}\text{Nd}_y\text{K}_{0.04}\text{MnO}_3$: Origin and effects on the colossal magnetoresistivity. *Europhys Lett*, 2000, 52: 441–447
- 21 Laiho R, Lisunov K G, Lahderanta E, et al. Influence of the phase separation effect on low-field magnetic properties of $\text{La}_{1-x}\text{Ba}_x\text{MnO}_3$. *J Magn Magn Mater*, 2005, 293: 892–902
- 22 Michael F. Ferromagnetic resonance of ultrathin metallic layers. *Rep Prog Phys*, 1998, 61: 755–826
- 23 Belmeguenai M, Mercone S, Adamo C, et al. Temperature dependence of magnetic properties of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3/\text{SrTiO}_3$ thin films on silicon substrates. *Phys Rev B*, 2010, 81: 054410
- 24 Lofland S E, Bhagat S M, Ju H L, et al. Ferromagnetic resonance and intrinsic properties of $\text{La}_{0.67}\text{Ba}_{0.33}\text{MnO}_3$. *J Appl Phys*, 1996, 79: 5166–5168
- 25 Song Y Y, Kalarickal S, Patton C E. Optimized pulsed laser deposited barium ferrite thin films with narrow ferromagnetic resonance linewidths. *J Appl Phys*, 2003, 94: 5103–5110
- 26 Seavey M H, Tannenwald P E. Direct observation of spin-wave resonance. *Phys Rev Lett*, 1958, 1: 168–169
- 27 Aleshkevych P, Baran M, Szymczak H. Magnon excitations in manganites. *Acta Phys Polonica A*, 2004, 106: 593–602

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.