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Effects of residual and tunable strain in thin films of La_{0.7}Ba_{0.3}MnO_3

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The effects of residual and tunable strain in thin films of La_{0.7}Ba_{0.3}MnO_3 (LBMO) were investigated. Different residual strains were achieved by depositing LBMO films with various thicknesses on 0.7PbMg_{1/3}Nb_{2/3}O_3–0.3PbTiO_3 (PMN-PT) and SrTiO_3 (STO). For LBMO on PMN-PT, when the thickness changes the resistance evolves dramatically. All samples on STO have a clear metal-to-insulator transition near room temperature. The tunable strain was modulated through the converse piezoelectric effects of PMN-PT. Clear voltage-controlled resistance modulations (|ΔR|/R_{max} ~ 90%) were observed in LBMO/PMN-PT. The magnitude and nonlinearity of elastoresistance are the largest in the thinnest sample. |ΔR|/R decreases as the thickness increases and is still substantial even the film is as thick as 150 nm. For thicker samples, the nonlinearity becomes weaker and the resistance changes linearly with voltage approximately. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4796050]

Perovskite manganese oxides have attracted continuing attention for decades due to their striking magnetic and electric properties.\(^1\)–\(^3\) Such materials can exhibit huge responses to applied magnetic fields.\(^4\)–\(^5\) The great sensitivity largely originates from the cross coupling between different physical degrees of freedoms (charge, spin, orbital, and lattice). One manifestation of the complex coupling is that manganites can be affected in a number of ways: chemical doping, pressure, light illumination, magnetic field, electric field, lattice strain, and etc.\(^6\)–\(^9\) Since the lattice strain is frequently present in the growth of thin films, it is very important to understand the strain effects. Conventionally, to study the strain effects, one can compare films with various thicknesses on the same substrate or with identical thickness on different substrates.\(^10\)–\(^12\) Varying thickness could tune the lattice parameter in a small range. Changing substrates could make the strain state be discrete values in a wider range. One concern about these two methods is that the variation of a second parameter, such as oxygen nonstoichiometry may have sizeable effects\(^13\)–\(^14\) which are hard to quantify. Employing the converse piezoelectric effect of piezoelectric substrates is a recently developed route to evaluate the strain effects.\(^15\)–\(^19\) Its achievable strain range is not large, but the strain can be continuously and reversibly tuned. Considering the advantages and disadvantages of these methods, a combination of them may become advantageous. Considering the advantages and disadvantages of these methods, a combination of them may be beneficial.

Effects of residual and tunable strain in thin films of La_{0.7}Ba_{0.3}MnO_3 (LBMO) were investigated. Different residual strains were achieved by depositing LBMO films with various thicknesses on 0.7PbMg_{1/3}Nb_{2/3}O_3–0.3PbTiO_3 (PMN-PT) and SrTiO_3 (STO). For LBMO on PMN-PT, when the thickness changes the resistance evolves dramatically. All samples on STO have a clear metal-to-insulator transition near room temperature. The tunable strain was modulated through the converse piezoelectric effects of PMN-PT. Clear voltage-controlled resistance modulations (|ΔR|/R_{max} ~ 90%) were observed in LBMO/PMN-PT. The magnitude and nonlinearity of elastoresistance are the largest in the thinnest sample. |ΔR|/R decreases as the thickness increases and is still substantial even the film is as thick as 150 nm. For thicker samples, the nonlinearity becomes weaker and the resistance changes linearly with voltage approximately. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4796050]

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There are clear evolutions of peak intensity, position, and shape with thickness. With the increase of film thickness, the diffraction peak becomes more asymmetric. This behavior is possibly due to the inhomogeneous strain as a result of strain relaxation. As the thickness increases from 15 nm to 150 nm, the out-of-plane lattice parameter increases from $a_{\text{LBMO}} \approx 3.862$ Å to $a_{\text{LBMO}} \approx 3.901$ Å. At the same time, R(T) curves also change dramatically [see Fig. 1(c)]. For LBMO on PMN-PT with a thickness of 15 nm, the resistance is greatly enhanced. As the temperature is lowered, the resistance increased monotonously. No metal-to-insulator transition can be found. The resistance in thicker films is smaller in the whole temperature range. For LBMO on PMN-PT with thicknesses of 60 nm and 150 nm, clear metal-to-insulator transition can be seen. For film with an intermediate thickness ($t = 30$ nm), with decreasing temperature, there is an insulator-to-metal transition slightly below room temperature and a low-temperature upturn of resistance in the R(T) curve.

For all LBMO films on STO, there are strong overlaps of reflection peaks for LBMO and STO (not shown). This is because the lattice parameter of bulk LBMO ($a_{\text{LBMO}} \approx 3.916$ Å) is very close to that of STO ($a_{\text{STO}} \approx 3.905$ Å). As a result of such overlaps, it is difficult to obtain the evolutions of peak intensity, as well as position and shape, when the thickness varies. As shown in Fig. 1(d), all LBMO films on STO have a clear metal-to-insulator transition near room temperatures, which does not change much as the thickness varies. The transition temperatures are close to that reported by Zhang et al. Compared to that on PMN-PT, the resistivity of LBMO on STO is much smaller. Since LBMO with the same thickness on PMN-PT and STO were deposited with identical parameters, the differences in transport properties should be mainly due to the effects of residual strain.

The schematic diagram for measuring transport properties is depicted in the inset of Fig. 2(a). The polarity in the schematic diagram is defined as positive. PMN-PT was poled by a $+500$ V voltage ($E = 10$ kV/cm) across PMN-PT. It was in the $P_{\text{r+}}$ state after the poling electric field was removed. To study the effects of tunable strain, the temperature dependences of resistance for LBMO were recorded with different positive bias voltages. As shown in Fig. 2, for all LBMO films, clear changes can be found in the R-T curves as the voltage varied. It is interesting to note that an electric field of $+10$ kV/cm ($V = 500$ V) almost completely suppressed the upturn of resistance at low temperatures [see Fig. 2(b)].

The temperature dependences of resistance modulation under a fixed voltage, $\delta(V) = |\Delta R/R = |\Delta R(V)/R(0)| = 100\% \times |[R(V)-R(0)]/R(0)|$, are presented in Fig. 3. There are clear differences for LBMO and PSMO. While for all PSMO films, $|\Delta R/R$ peaks are at a temperature slightly lower than $T_p$, for all LBMO films $|\Delta R/R$ increases as temperature decreases. Although there are clear metal-to-insulator transitions in LBMO films with thicknesses of 60 and 150 nm, only
anomaly but no clear peak is found in the temperature dependencies of $|\Delta R/R|$. There are also several similarities for LBMO and PSMO. The relative resistance changes $|\Delta R/R|$ in the thinnest film is the largest. For LBMO with a thickness of 15 nm, the maximum value of $|\Delta R/R|$ is $\sim 90\%$ at low temperatures. With increasing thicknesses, $|\Delta R/R|$ becomes smaller. For the film with a large thickness, e.g., $t = 150$ nm, $|\Delta R/R|$ is still considerable. Another prominent similarity is that, for films with small thicknesses, the change of resistance as the voltage decreases from 100 V to 0 V is different from that when the voltage drops from 500 V to 0 V. This means a nonlinear relation between $|\Delta R/R|$ and $V$.

The nonlinearity can be clearly seen from the voltage dependence of normalized resistance change, $\delta_n = \delta(V)/\delta(500 \text{ V})$, at selected temperatures. Figures 4(a) and 4(b) plot $|\Delta R/R|$ and $\delta_n$ as a function of applied voltage at 100 K. To get some insights, we use two quantities defined in Ref. 22, the additional area $\Delta s$ and the standard deviation $\sigma$, to characterize the nonlinearity. For the convenience of calculation, the voltage was normalized by 500 V. The additional area $\Delta s$ can be determined from the formula:

$$\Delta s = 0.2 \sum_{i=1}^{5} \delta_n(100i) - 0.6.$$ 

The standard deviation $\sigma$ examines the deviation from a linear $\delta_n$-$V$ curve:

$$\sigma = \sqrt{\sum_{i=1}^{5} \left[ \delta_n(100i) - 0.2 \right]^2}.$$ 

For a linear resistance-voltage relation, both $\Delta s$ and $\sigma$ should be 0. The strong nonlinearity in LBMO with a thickness of 15 nm is evidenced from the large values of $\Delta s$ and $\sigma$ at all temperatures. For LBMO films with larger thicknesses, the nonlinearity is less significant. The temperature dependences of $|\Delta R/R|$, $\Delta s$, and $\sigma$ are also very similar, suggesting close relations between these quantities. The similarities in temperature evolutions of $|\Delta R/R|$, $\Delta s$, and $\sigma$ were observed in PSMO, where it is suggested that phase competition significantly enhance both the magnitude and nonlinearity of elastoresistance. For LBMO studied in this paper, the increase of $|\Delta R/R|$ at low temperatures cannot be attributed to the enhancement of piezoelectric strain, which decreases slightly while the temperature is lowered. Possibly, the simultaneous rises in $|\Delta R/R|$, $\Delta s$, and $\sigma$ during cooling reflect more prominent phase competition at lower temperatures. It appears that the residual strain favors an insulating conduction and considerable insulating parts preserved even at low temperatures. This may be the reason that there is no peaks in temperature dependence of $|\Delta R/R|$, $\Delta s$, and $\sigma$.

To conclude, the effects of residual and tunable strain on the transport properties in thin films of LBMO are studied. For thin films of LBMO on PMN-PT, both the XRD reflection peaks and temperature dependence of resistance evolve dramatically when the thickness varies. On contrary, the transport properties in LBMO films on STO have no substantial dependence on thickness. Tunable strain effects in LBMO/PMN-RT were studied by employing the converse piezoelectric effects of PMN-PT. Clear resistance modulations were observed. For thinnest LBMO film, the strong nonlinearity is evidenced from the large values of $\Delta s$ and $\sigma$. The nonlinearity becomes weaker with increasing thicknesses. There are similarities in the temperature dependences of $|\Delta R/R|$, $\Delta s$, and $\sigma$ for LBMO on PMN-PT.

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