The effect of phase separation on the temperature dependent magnetoresistance in perovskite oxide heterojunction

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The interesting behavior of the magnetoresistance at various temperatures for the heterojunction of $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ is well explained based on the phase separation scenario. The good agreement between the theoretical and experimental results reveals that the mechanism for the variation in magnetoresistance with temperature and with the magnetic field is the competition between the positive magnetoresistance in the paramagnetic phase caused by the interface effect of the $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ *p-n* heterojunction and the negative magnetoresistance in the ferromagnetic phase of the $La_{0.9}Sr_{0.1}MnO_3$ film, respectively. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3003864]

Since the colossal magnetoresistance (CMR) effect has been observed in the perovskite manganites,[1] many research works are focused on the transport mechanism of this kind of material. The phase separation mechanism has been introduced to explain the CMR effect in manganite material.[2] In experiment, the phase separation phenomenon was observed in many kinds of perovskite manganites, such as $La_{1-x}Sr_xMnO_3$,[3] $La_{2/3}Ca_{1/3}MnO_3$,[4] $Pr_{1-x}Sr_xMnO_3$,[2] $Nd_{1-x}Sr_xMnO_3$,[5] and $La_{0.33}Pr_{0.34}Ca_{0.33}MnO_3$.[6] The $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ (LSMO/SNTO) *p-n* junction has been fabricated by laser molecular beam epitaxy and a novel temperature dependent magnetoresistance property was observed in this junction.[7] The Sr-doped $LaMnO_3$ has been widely known as a kind of material with negative magnetoresistance (MR) by the definition of $MR=[R(H)-R(0)]/R(0)$ with $R(0)$ and $R(H)$ denoting the resistance without and with magnetic field, respectively.[8] The interesting phenomenon is that in the LSMO/SNTO heterojunction, the MR behaves with a negative characteristic at low temperature of 100 K with large magnetic field and represents a positive MR property at the temperature range from 150 to 300 K with magnetic field below 5 T. That variation in MR value from negative to positive with temperature challenges the traditional understanding of the mechanism for the CMR effect. Although the physics origin of the positive MR at a given temperature has been revealed as the competition between the tunneling rate of electrons in the $e_g^1\uparrow$ band to $t_{2g}\downarrow$ band and that to $e_g^2\uparrow$ band at the interface region of $La_{0.9}Sr_{0.1}MnO_3$,[9] the intrinsic mechanism of this unusual variation from negative to positive MR with a large variation in temperature still remains unknown. In the present paper, a combination of this positive MR model and the phase separation mechanism is proposed to explain the temperature dependent MR of LSMO/SNTO heterojunction. The present results reveal that the variation in the MR in the temperature range from 100 to 300 K is attributed to the competition between the positive MR caused by the interface effect of the LSMO/SNTO heterojunction and negative MR of the LSMO film in the paramagnetic and ferromagnetic phases, respectively.

In the experiment, the *I-V* characteristics of the LSMO/SNTO *p-n* junction as a function of the applied magnetic field (0–5 T) were measured at $T=100$, 150, 200, and 300 K, respectively, and the CMR behavior was observed in the *p-n* junction. The CMR ratio is positive in magnetic field below 0.13 T at 100 K and at temperatures of 150, 200, and 300 K with magnetic field below 5 T, while it displays a negative CMR near 100 K with magnetic field larger than 0.13 T.[7]

To explain such an unusual CMR behavior, we employed the percolation mode on the basis of the phase separation mechanism in the LSMO/SNTO system. The phase separation means that the ferromagnetic metal phase and the paramagnetic insulator phase coexist at a given temperature.[10] The negative MR is mainly caused by the ferromagnetic phase owing to its intrinsic characteristic,[11] and the positive MR mechanism is attributed to the interface effect of LSMO/SNTO heterojunction.[9] In our previous paper,[9] the value of the positive MR at various spin polarization *P* is obtained, in which spin polarization *P* corresponds to the magnetic field in the experiment. The positive MR value increases with spin polarization and reaches a maximum value when the spin polarization reaches 1. In that case, the positive MR no longer increases with the increase in the magnetic field due to the saturation of spin polarization.

The typical size for the ferromagnetic phase cluster is about 0.6–1.1 μm at the temperature between 240 and 280 K.[12] In our transport measurement, the size of electrode is about 0.5 mm^2, and the electrode on the surface of LSMO is large enough to cover a large area with many ferromagnetic and paramagnetic phases as indicated in Fig. 1, so that current can be carried parallelly through various regions of the LSMO film. Due to the parallel connection of the resistance in the ferromagnetic and paramagnetic phases, the total resistance under the applied magnetic field R_H can be written as $R_H=R_{MH}R_{IH}/R_{MH}+R_{IH}$, where R_{MH} and R_{IH} being the resistance of ferromagnetic and paramagnetic phases under magnetic field, respectively. Moreover the total resistance under zero magnetic field is written as $R_0=R_{M0}R_{I0}/R_{M0}+R_{I0}$, where R_{M0} and R_{I0} are the resistance of ferromagnetic

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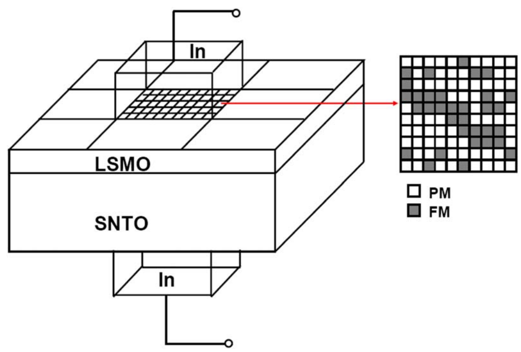

FIG. 1. (Color online) The schematic for the electrode on the measurement of the LSMO/SNTO heterojunction. In this figure, the electrode on the surface of LSMO is large enough to cover the clusters of ferromagnetic and paramagnetic phases, so that the current is parallel through various regions of the LSMO film.

and paramagnetic phases without magnetic field, respectively. At a given temperature and negative bias, the resistances of R_{I0} and R_{I0H} can be calculated by our model which was reported before.[9] The energy band structure of LSMO/SNTO heterojunction under −0.5 V bias at the temperature of 200 K for LSMO/SNTO junction is given in Fig. 2. The calculated results for the resistance of the paramagnetic phase with spin polarization at temperatures of 100, 150, 200, and 300 K are given in the inset of Fig. 3, respectively. By introducing the percolation mode,[13] the resistances of ferromagnetic phase R_{M0} and R_{MH} with and without magnetic field are obtained by $R_{M0(H)}=AR^{E}_{M0(H)}$, where $R^{E}_{M0(H)}$ is the experimental resistance obtained from Ref. 8, the parameter A is obtained from Monte Carlo simulation and is taken as 15.385. Moreover, based on the percolation mode the distribution of ferromagnetic and paramagnetic phases at temperatures of 100, 150, 200, and 300 K is given in Figs. 4(a)–4(d), respectively.[13] With the known value of $R_{M0(H)}$ and $R_{I0(H)}$, the total MR is calculated with the definition of $\mathrm{MR}=R_H-R_0/R_0$.

The positive MR dependence on spin polarization for paramagnetic phase at the temperature range of 100, 150, 200, and 300 K is calculated with the method reported in Ref. 9. The calculated curves of positive MR and the resistance of paramagnetic phase with spin polarization rate are given in Fig. 3 and the inset figure, respectively. As shown in Fig. 3, the positive MR value increases monotonously with the increase in spin polarization rate and decreases with the increase in temperature, respectively. Due to the Jahn–Teller distortion, the energy difference in ΔE between the bottom of the $e_g^2\uparrow$ band and the $t_{2g}\downarrow$ band decreases rapidly with the increase in temperature.[9] Moreover, the electron scattering from the $e_g^1\uparrow$ band to the $t_{2g}\downarrow$ band decreases with the decreases in energy difference ΔE. Therefore, the positive MR decrease with the increase in temperature.

The experimental and theoretical MR dependences on magnetic field at temperatures of 100, 150, 200, and 300 K are shown in Figs. 5(a) and 5(b), respectively. Figure 5(c) shows the calculated MR as a function of temperature with magnetic fields of 0.1, 1, 3 and 5 T, respectively. It is seen that the MR behaves with a negative characteristic at low temperature of 100 K with large magnetic field and represents a positive MR property at the temperature range from 150 to 300 K with magnetic field below 5 T. The behavior of CMR at various temperatures is explained based on the

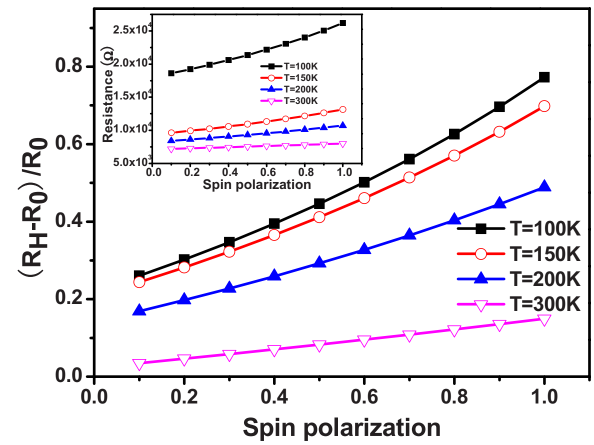

FIG. 3. (Color online) The positive MR dependence on spin polarization for paramagnetic phase at temperatures of 100, 150, 200, and 300 K, respectively in LSMO/SNTO *p-n* junction. The inset shows the resistance of the paramagnetic phase dependence on spin polarization.

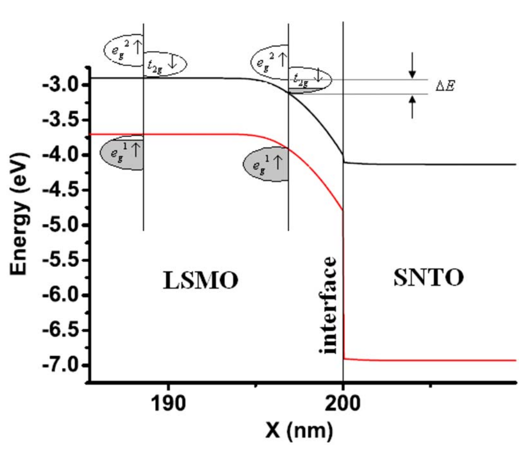

FIG. 2. (Color online) The energy band structure and the schematic density of states of the LSMO/SNTO junction at the −0.5 V bias.

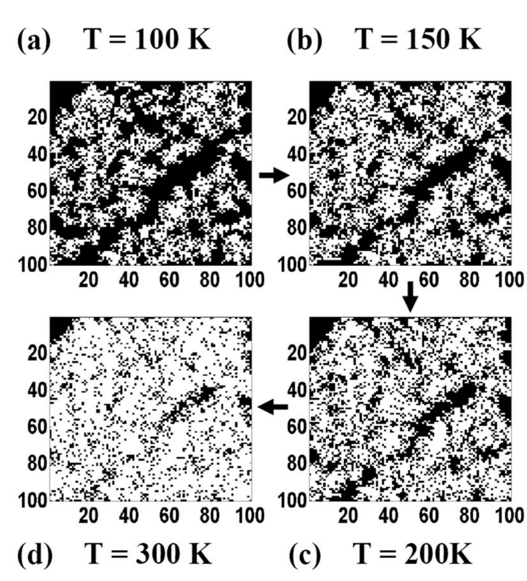

FIG. 4. Simulated process of cluster percolation from low temperature ferromagnetic phase (black) to high temperature paramagnetic phase (white) phase transition in the mixed-phase description on a 100×100 matrix at temperatures of 100 (a), 150 (b), 200 (c), and 300 K (d), respectively. The arrows indicate the warming process from 100 to 300 K.

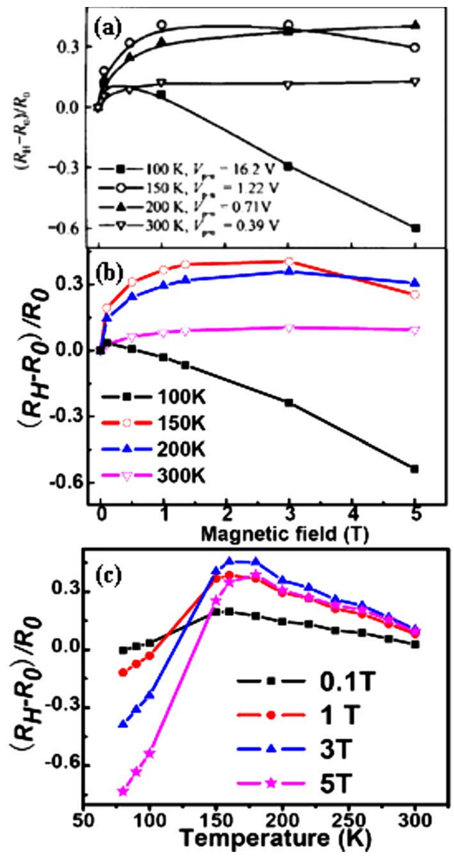

FIG. 5. (Color online) (a) The experimental MR dependence on magnetic field at the temperature range from 100 to 300 K in LSMO/SNTO *p-n* junction. (b) The calculated MR dependence on magnetic field at the temperature range from 100 to 300 K in LSMO/SNTO *p-n* junction. (c) The calculated magnetoresistance as a function of temperature with the magnetic fields of 0.1, 1, 3, and 5 T, respectively.

phase separation scenario and positive MR mechanism as follows. At the temperature of 100 K, the effect of positive MR on the paramagnetic phase is greater than that of the negative one on the ferromagnetic phase at magnetic field smaller than 0.13 T. Thus, the total MR displays a positive characteristic in this magnetic field region. With the increase in magnetic field, the value of negative MR increases rapidly and the negative MR becomes dominated. At temperatures of 150 and 200 K, the MR is positive, and it reaches a maximum value and then decreases with the increase in magnetic field. At low magnetic field, the value of positive MR is larger than that of negative ones. Therefore, the total MR increases with magnetic field. With the further increase in magnetic field, the positive MR is a constant value due to the saturation of spin polarization, while the absolute value of negative MR still increases. Thus the total MR decreases with further increase in magnetic field. Due to the much smaller proportion of ferromagnetic phase with that of paramagnetic phase in 300 K, as shown in Fig. 4(d), the contribution of negative MR to the total MR is very small, so that the total MR is positive under the magnetic field. Moreover, due to the saturation of spin polarization at higher magnetic field, the total MR is nearly a constant value with the increase in magnetic field.

In summary, the phase separation scenario is introduced to explain the mechanism of the MR with magnetic field in LSMO/SNTO *p-n* junction at various temperatures. The good agreement between theoretical and experimental data reveals the mechanisms of the novel temperature dependent MR behavior of LSMO/SNTO heterojunction, which is the competition between the positive MR caused by the interface effect in the LSMO/SNTO heterojunction in the paramagnetic phase and the negative MR in the LSMO film in the ferromagnetic phase.

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