Rapid Communication

The Sr content influence on the positive magnetoresistance in $La_{1-x}Sr_xMnO_3$/Si heterojunctions*

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We fabricated $La_{1-x}Sr_xMnO_3$/Si (LSMO/Si) heterojunctions with different Sr doping concentrations (x = 0.1, 0.2, 0.3) in LSMO and studied the Sr content influence on magnetoresistance (MR) ratio. The heterojunctions show positive MR and high sensitivity of MR ratio in a low applied magnetic field. The MR ratio is dependent on Sr content and the low Sr doping in LSMO causes a large positive MR in LSMO/Si junctions. The MR ratio for 0.1 Sr doping in the LSMO/Si heterostructure is 116% in 100 Oe (1 Oe=79.5775 A/m) at 210 K. The mechanism for the positive MR dependence on the doping density is considered to be the competition between the tunneling rate of electrons in $e_g^1\uparrow$ to $t_{2g}\downarrow$ band and that to $e_g^2\uparrow$ band at the interface region of LSMO. The experimental results are in agreement with those observed in $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ p–n junction. The results indicate that choosing low doping concentration to improve the low field sensitivity of the heterojunction devices is a very efficacious method.

Keywords: heterojunctions, magnetoresistance
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1. Introduction

Since the discovery of colossal magnetoresistance (CMR) phenomena in manganite thin films, much attention has been focused on the fabrication and the mechanism study of artificially designed structures to verify device concepts based on manganite thin films. The magnetoresistance (MR) ratio is defined as $(R_H - R_0)/R_0\times100\%$, where R_H is the resistance under the applied magnetic field and R_0 is the resistance in zero field. Some large MR ratios have been reported, such as –150% in $La_{0.8}Sr_{0.2}MnO_3/SrTiO_3/La_{0.8}Sr_{0.2}MnO_3$ at 5 K under a low switching field (< 10 Oe),[1] −450% in $La_{0.67}Ca_{0.33}MnO_3$/yttrium-stabilized zirconia/Si at 14 K in 200 Oe,[2] −23% in $La_{0.67}Ca_{0.33}MnO_3$/yttrium-stabilized zirconia/Si at 175 K in 1 T,[3] −35% in $[(Pr_{0.85}Ca_{0.15}MnO_3)_{10}(Ba_{0.6}Sr_{0.4}TiO_3)_9]_{25}$ superlattice at 100 K in 7 T,[4] 25% in $Fe_3O_4/SrTiO_3/La_{0.7}Sr_{0.3}MnO_3$ at 80 K in 4 T,[5] ∼ 1800 in $Pr_{0.6}Ca_{0.4}MnO_3$/Nb-$SrTiO_3$ at 265 K in 5 T,[6] 65% in $La_{0.6}Pr_{0.2}MnO_3$/Nb-$SrTiO_3$ at 300 K in 8 T,[7] and a large positive MR in $La_{0.7}Ca_{0.3}MnO_3/SrTiO_3/La_{0.7}Ce_{0.3}MnO_3$ at 48 K in 2 T.[8] All most the large MRs observed are in a low temperature or under a high magnetic field. We reported the unusual positive MR effects, 23% in $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ p–n junctions at 290 K in 100 Oe,[9] 40% in multi-p–n heterojunction of $La_{0.9}Sr_{0.1}MnO_3$ and oxygen-vacant $SrTiO_{3-\delta}$ on Si substrate at 300 K in 200 Oe, as well as the electrical-modulated MR.[10] A mechanism based on the spin scattering near the interface region has been proposed to explain such an unusual positive MR property of the all perovskite oxide heterostructures.[11] In addition, limited research groups grow the MR manganites on Si substrates to combine the manganite films with Si semiconductor. Sheng *et al.* observed −50% MR in $La_{2/3}Sr_{1/3}MnO_{3-\delta}$/Si at 200 K in 5 T.[12] Hu *et al.* reported MR in $La_{0.9}Ba_{0.1}MnO_3$/Si at 72–175 K in 5 T.[13] Cho *et al.* prepared $La_{0.85}Sr_{0.15}MnO_3$ film on SiO_2/Si and got −10.8% MR at 268 K in 1.5 T, and the MR did not change much with Sr content.[14] From a practical point of view, useful devices must operate at higher temperatures preferable near room temperature and in modest fields of

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$H < 0.1$ T. Thus it is highly desirable to obtain large MR ratio at high temperature and low applied magnetic field. As mentioned above, it is notable that the experimental results show that the doping density in the manganite thin films plays a very important role for MR ratio. Although Sr-doped lanthanium manganites ($La_{1-x}Sr_xMnO_3$) has been extensively investigated,[15−18] as we know, no systematic characterization for MR dependence of Sr content in heterostructures has been available yet. In this paper, we study the influence of Sr doping density on MR ratio in $La_{1-x}Sr_xMnO_3$/Si (LSMO/Si, $x = 0.1$, 0.2, or 0.3) heterostructures. Our experimental results proved that the positive MR in $La_{1-x}Sr_xMnO_3$ with lower doping is larger than that with higher doping in the LSMO/Si heterostructures.

2. Experiments

As mentioned in our previously report,[9,19] the LSMO thin films with different Sr content ($x = 0.1$, 0.2, or 0.3) were epitaxially on n-type Si substrates with a resistivity of 4.2 Ω·cm by a computer-controlled laser molecular-beam epitaxy.[20] The thickness of the LSMO films was 400 nm for various samples. We have reported the structure characteristics,[19] photoelectric effects[21−23] and transport property of LSMO/Si heterostructures.[24] The measurement results of *in situ* RHEED and *ex situ* XRD indicate that the LSMO films are single phase and epitaxially grown on the Si substrates. In this paper, we focus on the Sr content influence on MR in LSMO/Si heterojunctions.

We measured the LSMO/Si heterojunctions in a temperature range of 210–335 K and under applied magnetic fields varying between 0 and 1 T by a superconducting quantum interference device (SQUID, Quantum Design MPMS 5.5 T). The sizes of the samples are 2×2 mm^2. Indium electrodes were attached to the surfaces of LSMO thin film and Si substrate as shown in the inset of Fig. 1. The magnetic field H was applied perpendicular to the interface of the heterojunction.

3. Results and discussion

Figure 1 shows the negative bias MRs of LSMO/Si ($x = 0.1$, 0.2, 0.3) heterojunctions as a function of temperature under 100 Oe applied magnetic field with a 10-μA pulse-modulated current source. Similar to the all perovskite oxides p–n junctions reported previously,[9−11] the heterojunctions have positive MR ratios and high sensitivity in a low applied magnetic field. The MRs are positive and decrease with increasing temperature. From Fig. 1, we can see that the MR ratios vary with the different Sr doping, and the LSMO/Si heterostructures with lower Sr doping concentration ($x = 0.1$) have much larger MR than those with higher Sr doping concentration ($x = 0.2$, 0.3) in LSMO thin films. The positive MRs reach as large as 116%, 38% and 30% at the temperature of 210 K for the Sr doping of 0.1, 0.2, and 0.3 in the LSMO/Si heterostructures, respectively.

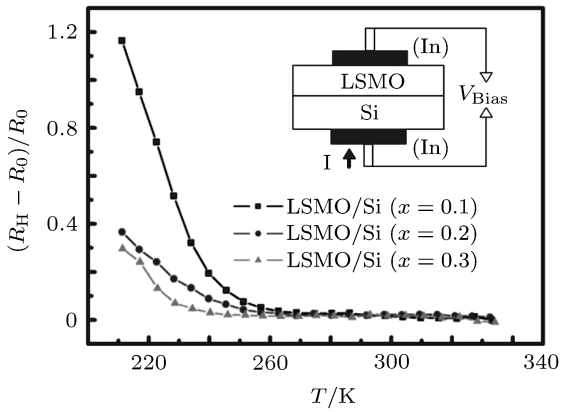


Fig. 1. Temperature dependence of MR ratios of LSMO/Si ($x = 0.1$, 0.2, 0.3) heterojunctions under 100 Oe magnetic field. Schematic circuit of the sample measurement is shown in the inset.

As we know, $La_{0.9}Sr_{0.1}MnO_3$/Si heterojunction is a semiconducting p–n junction because $La_{0.9}Sr_{0.1}MnO_3$ film has a semiconducting property, and $La_{0.7}Sr_{0.3}MnO_3$/Si heterojunction is a Schottky junction because $La_{0.7}Sr_{0.3}MnO_3$ film has a metal-like behaviour. We think the key point of these interesting phenomena is based on the interface effects of the LSMO/Si heterostructures.[9−11] To understand such unusual positive MR behaviour in low magnetic fields, we plotted the schematic density of states (DOS) of the LSMO/Si heterojunctions and the energy band diagrams at reverse bias as shown in Fig. 2. Such positive MR can be understood by spin scattering of electrons in the tunneling process of the carriers in the $e_g^1 \uparrow$ band from the homogeneous region into the $t_{2g} \downarrow$ band in space charge region of LSMO near the interface under applied reverse bias voltages.[9−11]

Higher doping concentration of Sr in LSMO results in a lower Fermi level in the LSMO thin film of LSMO/Si heterostructure. As schematically shown in Fig. 2, LSMO with 0.3 Sr doping has lower Fermi level than that with 0.1 at reverse bias. The lowering of the

Fermi level causes much decreasing of the carriers in the $e_g^1 \uparrow$ band from the homogeneous region tunneling into the $t_{2g} \downarrow$ band in space charge region of LSMO near the interface under applied reverse bias voltages, as a result, the positive MR decreases. This is why the heterostructures of LSMO/Si with the lowest doping concentration of Sr ($x = 0.1$) show the largest positive MR.

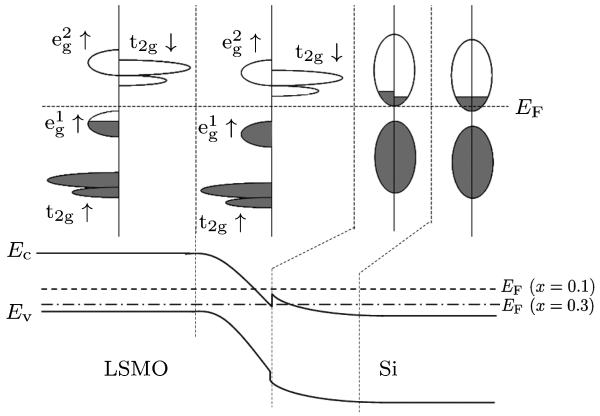


Fig. 2. Schematic electron DOS of the LSMO/Si heterojunctions and the energy band diagram for x being 0.1 and x being 0.3 at reverse bias. The Fermi level when x being 0.1 and 0.3 are denoted by dash-dot line and black dash line, respectively.

The MR of the $La_{0.9}Sr_{0.1}MnO_3$/Si heterojunction as a function of temperature under different magnetic fields is plotted in Fig. 3. It is always positive and decreases abruptly with increasing temperature in the low temperature region around 210–250 K. This trend is attributed to the transition from ferromagnetic metal phase to paramagnetic insulator phase in LSMO. Since the paramagnetic insulator phase becomes dominant with the increased temperature, the positive MR decreases.[25−27] The MR reaches 116%, 125% and 111% in the applied magnetic fields of 100 Oe, 1000 Oe, and 1 T at 210 K, respectively. If we keep on increasing the temperature, the MR turns negative in high temperature region from 250 K to 320 K. The MR becomes −0.6%, −2.5%, and −5% in the applied magnetic fields of 100 Oe, 1000 Oe and 1 T at 320 K, respectively. The variation in the MR with temperature and with the magnetic field is attributed to the competition between the positive MR caused by the interface effect of the LSMO/Si heterostructure and negative MR of the LSMO films in the paramagnetic and ferromagnetic phases, respectively.[25−27]

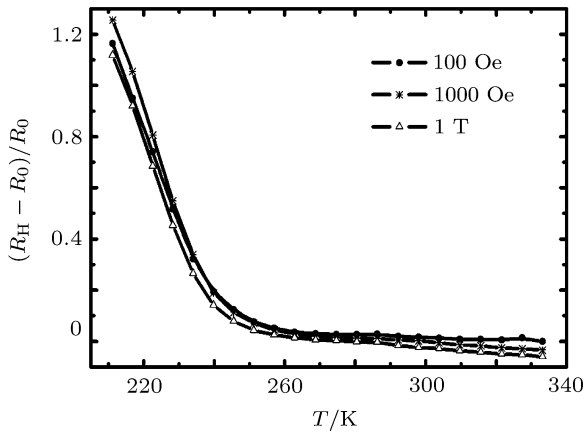


Fig. 3. Temperature dependence of the MR ratio of $La_{0.9}Sr_{0.1}MnO_3$/Si heterojunction in external magnetic fields of 100 Oe, 1000 Oe and 1 T.

4. Conclusions

In summary, we studied the Sr content influence on MR ratios in LSMO/Si heterojunctions with different Sr doping concentrations ($x = 0.2$, 0.3) in LSMO. The positive MR and high sensitivity of MR ratios in low applied magnetic field are observed. The MR ratios are dependent on Sr content and the low Sr doping in LSMO causes a large positive MR in LSMO/Si junctions. The high sensitivity of positive MR of the heterojunctions in low magnetic field is related to the interface of the junction. The experimental results are in agreement with those we observed in $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$ p–n junction.[9] It is proved that the choice of low doping concentration to improve the low field sensitivity of the heterojunction devices is a very efficacious method. In addition, it is noteworthy that the heterojunctions combine the magnetic function of LSMO with Si semiconductor, and suggest the possibility to develop the magnetically controllable functional electric devices based on conventional semiconductors Si and manganese oxides.

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