Spin-dependent and spin-independent channels of electrical transport in perovskite manganites

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A model with two channels of electrical transport (TCET) for perovskite manganites is proposed, and it is described by an equivalent device with two current-carrier channels. In one channel, there is a spin-independent resistor ($R_s$) with an equivalent resistivity of $\rho_s$. In the other channel, there are two spin-dependent resistors in series ($R_1$ and $R_2$) with an equivalent resistivity of $\rho_1 + \rho_2$. The component $\rho_s$ includes residual resistivity and the resistivity contributed by crystal-lattice scattering. The other component of the equivalent resistivity, $\rho_i$, originates from the spin orientations of the itinerant electrons and the local electrons of the outer O 2p and Mn 3d orbits that deviate from the orientation of their ground states when the test temperature is close to the Curie temperature. Using this model, we fitted the experimental curves of the resistivity versus test temperature for single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ (0.00 $\leq x \leq 0.40$) and polycrystalline La$_{0.7}$Sr$_{0.3}$Mn$_{1-x}$Fe$_x$O$_3$ (0.00 $\leq x \leq 0.30$). In addition, we investigated the effects of the fraction of the antiferromagnetic phase, scattering at the crystallite interfaces, and the crystal-cell constants on the samples’ resistivity. The physical mechanism of the TCET model was explained using an O 2p itinerant-electron model, which has been used in other studies to explain the magnetic ordering of several series of spinel ferrites and perovskite manganites.

1. Introduction

There have been many investigations on the electronic transport and magnetic properties of perovskite oxides1-12 because of their potential application in both electronic and magnetic information-storage devices. There are several models for the electronic-transport properties of these materials, and spin-dependent transport has been taken into account by most researchers. One of the popular views is that there is polaron hopping below the Curie temperature ($T_C$) on the basis of the double-exchange interaction.2,13 In this view, the current carriers of perovskite manganites originate from the d electrons of manganese cations. Another view was proposed by Alexandrov et al.13,14 who argued that the current carriers of perovskite manganites originate from the p holes of oxygen anions rather than the d electrons of manganese cations, based on the experimental results of electron-energy-loss spectroscopy15,16 and X-ray absorption spectroscopy.17 Alexandrov et al.13,14 therefore established a current-carrier-density collapse (CCDC) model for the electrical-transport mechanism, and many researchers followed with investigations on this CCDC model.18-21

The presence of p holes of oxygen anions in an oxide can be easily understood as there are O$^{1-}$ anions in addition to O$^{2-}$ anions. When compared with an O$^{2-}$ anion (2s$^2$2p$^6$) with a closed outer electron shell, it is clear that a p hole exists in the outer orbit of an O$^{1-}$ anion (2s$^2$2p$^5$). This fact was further confirmed by theoretical calculations22,23 and experiments.24-26

Taking into account that there are both O$^{1-}$ and O$^{2-}$ anions in oxides,22-27 our group has proposed an O 2p itinerant-electron model for magnetic oxides (IEO model),28-32 which is similar to the O 2p hole model proposed by Alexandrov et al.13,14. Using the IEO model, our group studied the relationship between the magnetic moment and cation distribution of several series of Cr (Ti, Mn)-doped spinel ferrites.33-36 We also studied the magnetic ordering in perovskite manganites.37-40

In this study, we used a model of two channels of electrical transport (TCET), which was derived from the IEO model, to fit the temperature dependence of the resistivity for two series of perovskite manganites: single crystallines La$_{1-x}$Sr$_x$MnO$_3$ (0.00 $\leq x \leq 0.40$) reported by Urushibara et al.44 and polycrystallines La$_{0.7}$Sr$_{0.3}$Mn$_{1-x}$Fe$_x$O$_3$ (0.00 $\leq x \leq 0.30$) prepared in this work. In addition, we will discuss the effects of the proportion of the antiferromagnetic phase, scattering at crystallite interfaces, and crystal-cell constants on the samples’ resistivity.

2. Experiment and results

The polycrystalline perovskites examined in this study, La$_{0.60}$Sr$_{0.40}$Fe$_x$Mn$_{1-x}$O$_3$ (0 $\leq x \leq 0.3$), were prepared using the sol–gel method:45,46 (i) stoichiometric amounts of La$_2$O$_3$ (purity: 99.99%, fired in air at 1073 K for 3 h before it was used),
Sr(NO$_3$)$_2$ (purity: 99.5%) powder, and a Mn(NO$_3$)$_2$ solution (purity: 50%) were dissolved in a dilute HNO$_3$ solution at 343 K. Citric acid and ethylene glycol were added to the mixed solution as complexing agents until a completely homogeneous transparent solution was obtained. The molar ratio of citric acid (or ethylene glycol) to the perovskite molecule was 6 : 1. The mixture was then evaporated at 363 K for 24 h in a water bath until a highly viscous residue was formed. Upon further heating at 373 K for 12 h and then at 473 K for 24 h, a gel developed. The gel was ground. (iii) All ground gel samples of different compositions were further heat treated. The temperature was increased from 473 to 573 K, in increments of 25 K, with 45 min spent at each step. Next, the temperature was increased from 573 to 673 K in increments of 20 K, with 50 min spent at each step. Finally, the temperature was increased from 673 to 773 K in increments of 10 K, with 1 h spent at each step. The samples were finely ground for 30 min to obtain a homogeneous mixture. After that, the samples were calcined at 873 K for 5 h to eliminate the organic material, ground, and calcined again at 1073 K for 10 h to eliminate any residual organic material. Each sample was then divided into two parts to measure their magnetic and electrical properties, and they were subjected to further heat treatment using slightly different methods.

To prepare the samples used to measure the magnetic properties, the powder obtained after grinding was pressed into pellets with a diameter of 13 mm and thickness of about 2 mm under a pressure of 10 ton per cm$^2$. The pellets were calcined at 1273 K for 10 h, after which powder samples were obtained by grinding.

To prepare the samples used to measure the electrical-transport properties, the powder obtained after grinding was pressed into pellets under a pressure of 10 ton per cm$^2$. The pellet samples were then sintered at 1573 K for 24 h.

Table 1 Crystal structural parameters of La$_{0.6}$Sr$_{0.4}$Fe$_{x}$Mn$_{1-x}$O$_3$ at room temperature: $a$ and $c$ are the cell constants, $v$ is the cell volume, $d_{\text{Mn-O}}$ and $\Theta$ are the Mn–O distance and Mn–O–Mn bond angle, all which were obtained by fitting the XRD patterns; $s$ is the goodness-of-fit factor. $s_x$ and $\mu_{\text{abs}}$ are the specific saturation magnetization and the average molecular magnetic moment at 10 K, respectively. $T_C$ and $T_N$ are the Curie temperature and the Néel temperature, respectively; $T_{\text{MI}}$ is the temperature at which the resistivity has the maximum value.

<table>
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<th>$x$</th>
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<th>$c$ (Å)</th>
<th>$v$ ($Å^3$)</th>
<th>$d_{\text{Mn-O}}$ (Å)</th>
<th>$\Theta$ (°)</th>
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<th>$\mu_{\text{abs}}$ ($\mu_B$)</th>
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Fig. 1 (a) Powder XRD patterns of La$_{0.6}$Sr$_{0.4}$Fe$_x$Mn$_{1-x}$O$_3$. (b) Fitted and observed XRD patterns for the sample La$_{0.6}$Sr$_{0.4}$Fe$_{0.1}$Mn$_{0.9}$O$_3$, obtained using the Fullprof software. The crosses represent the observed data, and the curve represents the fitted results; the vertical bars represent the Bragg sites for the space group $R3c$. The difference between the observed and fitted patterns is shown at the bottom.
length, $d_{\text{B-O}}$ and the Mn–O–Mn bond angle, $\Theta$, are listed in Table 1. It can be seen that the values of these parameters slightly varied: the values of $a$, $c$, $v$, and $d_{\text{B-O}}$ increased with increasing $x$; and the value of $\Theta$ decreased with increasing $x$. The equivalent cubic cell constants ($a_{\text{eq}}$) per formula, calculated using the crystal-cell volume, $v$, will be used to discuss the samples’ resistivity in Section 4.4.

Fig. 2(a) shows the magnetic hysteresis loops of the samples measured at 10 K. Using the specific saturation magnetization, $\sigma_{\text{sat}}$, at 10 K, the average values of the molecular magnetic moment, $\mu_{\text{obs}}$, were obtained. Fig. 2(b) shows the curve of $\mu_{\text{obs}}$ versus $x$. Fig. 2(c) shows the curves of $\sigma$ versus $T$ under an applied magnetic field of 0.05 T. The values of the Curie temperature, $T_C$, defined as the temperature at which $d\sigma/dT$ reaches its minimum value, are shown in Fig. 2(d). In addition, the inset in Fig. 2(c) shows that there was a different Neél temperature, $T_N$, for each sample with $x \approx 0.20$. Below $T_N$, the value of $\sigma$ exhibited no significant change; above $T_N$, the value of $\sigma$ decreased distinctly. The variation of $T_N$ with $x$ is shown in the inset in Fig. 2(d). The values of $\mu_{\text{obs}}$, $T_C$, and $T_N$ are listed in Table 1.

The data points in Fig. 3 show the temperature dependence of the electrical resistivity, $\rho$, of the samples, and it can be seen that $\rho$ increased with increasing $x$. In addition, there was a resistivity peak at a characteristic temperature, $T_{\text{MI}}$, for each sample when $x \approx 0.15$, and these characteristic temperatures are listed in Table 1. The curves in Fig. 3 also show the fitted results, which will be discussed in the following sections.

The following trends can be observed in Fig. 2 and 3: (i) when $x \approx 0.15$, the samples were ferromagnetic conductors. The value of $\mu_{\text{obs}}$ decreased slowly from 3.194 $\mu_B$ ($x = 0.00$) to 2.887 $\mu_B$ ($x = 0.15$); the value of $T_C$ decreased rapidly from 364.5 K ($x = 0.00$) to 187.3 K ($x = 0.15$); the maximum resistivity increased from 0.0222 $\Omega$ cm ($x = 0.00$) to 4.47 $\Omega$ cm ($x = 0.15$). (ii) When $x \approx 0.20$, the samples were semiconductors with both an antiferromagnetic phase and a ferromagnetic phase. The resistivity increased rapidly with decreasing temperature, exceeding 100 $\Omega$ cm when the test temperature was below 123.6, 140.2, and 159.3 K, when $x = 0.20$, 0.25, and 0.30, respectively. In addition, when $x = 0.20$, 0.25, and 0.30, respectively, the values of $T_N$ of the antiferromagnetic phase were 40.5, 37.6, and 32.9 K; the Curie temperatures of the ferromagnetic phase were 68.9, 51.3, and 45.5 K; and the $\mu_{\text{obs}}$ values were 0.068, 0.065, and 0.036 $\mu_B$. 

Fig. 2 Magnetic properties of La$_{0.6}$Sr$_{0.4}$Fe$_{x}$Mn$_{1-x}$O$_3$: (a) magnetic hysteresis loops at 10 K; (b) magnetic moment, $\mu_{\text{obs}}$, at 10 K as a function of Fe content, $x$; (c) temperature dependence of the specific magnetization, $\sigma$, at an applied magnetic field of 0.05 T; (d) magnetic transition temperature as a function of Fe content, $x$. The insert of (c) enhanced the variations of the curves. The insert of (d) shows the Neél temperature, $T_N$, as a function of Fe content, $x$.

Fig. 3 Temperature dependence of electrical resistivity of the La$_{0.6}$Sr$_{0.4}$Fe$_{x}$Mn$_{1-x}$O$_3$ samples. The data points represent the observed values, and the curves represent the fitted results.
3. Model with two channels of electrical-transport (TCET) for perovskite manganites

In order to explain the electrical-transport properties of perovskite manganites, we propose a model with two channels of electrical transport (TCET), which was derived from the IEO model. The IEO model is based on the following three postulates: (i) in a given sublattice, an O 2p electron with a constant spin direction can hop from an O^2− anion to an O 2p hole belonging to an adjacent O^2− anion, with the metal cation acting as the intermediary. (ii) The two O 2p electrons in the outer orbit of an O^2− anion, which have opposite spin directions, become itinerant electrons of two different sublattices (such as the (A) and [B] sublattices of [A][B]O3 spinel ferrites, or the A and B sublattices of ABO3 manganites). (iii) Since an itinerant electron has a constant spin direction in a given sublattice and owing to Hund’s rules, the magnetic moments of cations with different sublattices, become itinerant electrons of two different sublattices (such as Mn^3+ or divalent and trivalent Cr cations), will couple antiferromagnetically with those of magnetic moments of cations with n_d ≥ 5, such as Mn^3+ or divalent and trivalent Fe, Co, and Ni cations. This occurs because in the 3d orbits of transition elements, a maximum of five electrons can have their spins aligned in the same direction.

It is well known that there are two sublattices in ABO3 perovskite manganites: the A-O sublattice and the B-O sublattice. According to the above IEO model, there are O-A-O-A-O and O-B-O-B-O ionic chains, which can be regarded as two current-carrier channels. In La_{1-x}Sr_xMnO_3, the movement of O 2p electrons along the first channel, i.e., the O-A-O-A-O (where La and Sr occupy the A sites) ionic chain, is a spin-independent process because there is no magnetic ordering. The resistance of the first channel is labeled R_1 (with an equivalent resistivity of \( \rho_1 \)). The movement of O 2p itinerant electrons along the second channel, i.e., the O-Mn-O-Mn-O (where Mn occupies the B site in O-B-O-B-O) ionic chain, is a spin-dependent process below the Curie temperature because there is magnetic ordering. The resistance of the second channel is represented by two resistors in series, \( R_2 \) and \( R_3 \) (with an equivalent resistivity of \( \rho_2 + \rho_3 \)), where \( \rho_1 \) includes the residual resistivity and the resistivity resulting from scattering by the crystal lattice, and \( \rho_2 \) originates from the spin orientations of the itinerant electrons and local electrons of the outer O 2p and Mn 3d orbits that deviate from the orientation of their ground states because of thermal fluctuation. Therefore, the TCET model for a perovskite manganite sample can be represented by the equivalent circuit shown in Fig. 4(a), with the resistance, \( R \), and resistivity, \( \rho \), defined as follows:

\[
R = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3}, \quad \rho = \frac{(\rho_1 + \rho_2)\rho_3}{\rho_1 + \rho_2 + \rho_3}
\]

A series of curves of \( \rho \) versus test temperature, \( T \), for single-crystalline La_{1-x}Sr_xMnO_3 (0.00 ≤ x ≤ 0.40) were reported by Urushibara et al., and they were fitted using the TCET model. As shown in Fig. 5, the fitted curves are very close to the observed results (data points).

When 0.175 ≤ x ≤ 0.40, we found that the resistivities in eqn (1) can be expressed as follows:

\[
\rho_1 = \rho_0 + a_1(T_1 + T)^2, \quad \rho_2 = a_2 \exp\left(\frac{E_1}{k_B T}\right),
\]

\[
\rho_3 = a_3 \exp\left(\frac{E_2}{k_B T}\right)
\]

where \( k_B \) is the Boltzmann constant. The parameters in eqn (2) were determined by fitting the experimental curves of \( \rho \) versus \( T \), and the results are listed in Table 2. For example, the parameters for the sample with x = 0.20 were determined as follows: first, it can be seen that the curve of \( \rho \) versus \( (T_1 + T)^2 \) can be approximated as a straight line at lower temperatures by adjusting the parameter \( T_1 \), as shown in Fig. 6(a). We then determined the residual resistivity, \( \rho_0 \), and the parameter \( a_1 \) from the intercept and slope, respectively, of the straight line in Fig. 6(a). Second, an approximate straight line of \( \ln \rho \) versus 1/\( k_B T \) can be seen at higher temperatures, as shown in Fig. 6(b). We obtained the approximate values of \( a_2 \) and \( E_1 \) from the intercept and slope, respectively, of the straight line in Fig. 6(b).
Table 2 Parameters of La$_{1-x}$Sr$_x$MnO$_3$ obtained by fitting the experimental curves of resistivity ($\rho$) versus test temperature ($T$) reported by Urushibara et al.$^{46}$ The $\rho_0$ is the residual resistivity in $\rho_1$. The $a_2$ and $T_1$ are the parameters (in the $\rho_2$) which result from scattering by the crystal lattice; the $a_3$ and $E_2$ are the parameters in the $\rho_2$ of the samples with $x = 0.10$ and 0.15. The $a_2$ and $E_2$ are the parameters (in the $\rho_3$) which originate from the spin orientations of the inner electron and local electrons of the outer O 2p and Mn 3d orbits that deviate from the orientation of their ground states because of thermal fluctuation. The $a_3$ and $E_3$ are the parameters (in the $\rho_3$) which originate from the spin-independent transition.

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<th>$a_{11}$ ((\Omega \text{ cm}))</th>
<th>$E_1$ (eV)</th>
<th>$a_2$ ((\Omega \text{ cm}))</th>
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Third, we determined the parameters $a_3$ and $E_3$ by fitting the curves of $\rho$ versus $T$. In this fitting process, the parameters $\rho_0$, $a_1$, and $T_1$ remained constant, but $a_3$ and $E_3$ required slight adjustments. The curves of observed $\rho$, and fitted $\rho_1$, $\rho_2$ and $\rho_3$ versus $T$ are shown in Fig. 6(c). Finally, the dependence of the observed (data points) and fitted (curve) $\rho$ of La$_{0.8}$Sr$_{0.2}$MnO$_3$ on the test temperature, $T$, is shown in Fig. 6(d). It can be seen that the fitted curve is very close to the observed results.

For the antiferromagnetic semiconductor samples with $x = 0.00$ and 0.05, the curves of $\rho$ versus $T$ can only be fitted by the equation $\rho = a_3 \exp \left( \frac{E_3}{k_B T} \right)$. The values of the fitted parameters $a_3$ and $E_3$ are listed in Table 2.

For the samples with $x = 0.10$ and 0.15, the curves of $\rho$ versus $T$ can be fitted using eqn (1) and (2), but the expression $\rho_1 = a_{11} \exp \left( \frac{E_1}{k_B T} \right)$ must substitute for $\rho_1$ in eqn (2). The values of the fitted parameters $a_{11}$, $E_1$, $a_2$, $E_2$, $a_3$, and $E_3$ are listed in Table 2.

For the polycrystalline samples of La$_{0.6}$Sr$_{0.4}$Fe$_{2}$Mn$_{1.4}$O$_3$ and La$_{0.6}$Sr$_{0.4}$MnO$_3$, also prepared by Urushibara et al., the transition probability of the itinerant electrons decreased rapidly and $\rho_3$ increased rapidly because the spin orientations of the itinerant electron deviated from the direction of their ground states. When $T$ was lower than $T_c$, the spin orientations of the itinerant electrons changed into disorder, and the electrical transport became spin-independent along both O–A and O–B–O–B–O–O ion chains.

### 4. Discussion

#### 4.1 Spin-dependent and spin-independent electrical transport in perovskite manganites, and their difference from free electron transport in magnetic metals

Fig. 6(c) shows that at lower temperatures, the spin-independent resistivity, $\rho_3$, of La$_{0.8}$Sr$_{0.2}$MnO$_3$ prepared by Urushibara et al. was so high that the electrical transport occurred along the spin-dependent channel, and the value of $\rho$ was close to $\rho_3$, which increased with increases in the test temperature $T$ owing to the thermal vibration of ions. When $T$ was close to $T_c$, the transition probability of the itinerant electrons decreased rapidly and $\rho_3$ increased rapidly because the spin orientations of the itinerant electron and the electrons in the outer O 2p and Mn 3d orbits deviated from the direction of their ground states. When $T$ was higher than $T_c$, the spin orientations of the itinerant electrons changed into disorder, and the electrical transport became spin-independent along both O–A–O–A–O and O–B–O–B–O–O ion chains.

It should be noted that the resistivity of La$_{0.6}$Sr$_{0.4}$MnO$_3$, also prepared by Urushibara et al., was 84 $\mu$ohm cm at 2 K, which is far higher than the resistivities of the magnetic metals Fe (8.6 $\mu$ohm cm), Ni (6.14 $\mu$ohm cm), and Co (5.57 $\mu$ohm cm). Therefore, it can be
Table 3 Parameters of La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ obtained by fitting the experimental curves of ρ versus T from this work. The $\rho_0$ is the residual resistivity in $\rho$. The $a_0$ and $T_a$ are the parameters (in the $\rho_0$) which result from scattering by the crystal lattice. The $a_2$ and $E_2$ are the parameters (in the $\rho_2$) which originate from the spin orientations of the itinerant electrons and local electrons of the outer O 2p and Mn 3d orbits that deviate from the orientation of their ground states because of thermal fluctuation. The $a_4$ and $E_4$ are the parameters (in the $\rho_4$) which originate from the spin-independent transition. All these parameters include the effect of the crystallite interfaces.

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Concluded that the spin-dependent transport of itinerant electrons in perovskite manganites below $T_C$ is distinctly different from the spin-independent transport of free electrons in magnetic metals.

4.2 Effect of proportion of the antiferromagnetic phase on the resistivity of La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ (0.00 ≤ x ≤ 0.30)

Our previous investigation$^{37-38}$ showed that all Mn and Fe ions are trivalent in La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$. According to the IEO model, an itinerant electron with up-spin in a sample with no Fe doping moves along the O$^2-$–Mn$^{3+}$–O$^{1-}$–Mn$^{3+}$–O$^2-$ ion chain, which always occupies the highest energy level whenever it reaches a Mn$^{3+}$ or O$^2-$ ion, as shown in Fig. 7(a). In this transition process, the itinerant electron consumes a small fraction of the energy of the system. When an itinerant electron with up-spin moves along the O$^2-$–Fe$^{3+}$–O$^{1-}$–Mn$^{3+}$–O$^2-$ ion chain, it always occupies the highest energy whenever it reaches a Mn$^{3+}$ or O$^2-$ ion, but the lowest energy level of an Fe$^{3+}$ ion, as shown in Fig. 7(b), because the Fe$^{3+}$ (3d$^5$) cation couples antiferromagnetically with the Mn$^{3+}$ (3d$^5$) cation (see the IEO model). In this transition process, the itinerant electron must consume more energy of the system, resulting in lower transition probability for the itinerant electrons and increased resistivity. Therefore, the resistivity increases with increasing proportion of the antiferromagnetic phase. As shown in Fig. 7(a and b), the spin orientation of the majority of 3d electrons in Mn$^{3+}$ cations is up; the spin orientation of the majority of local 3d electrons in Fe$^{3+}$ cations and local O 2p electrons in O$^{1-}$ anions is down.

![Fig. 7 Schematic diagrams of the transit of itinerant electrons in a spin-dependent process. (a) An itinerant electron with up-spin moves along the O$^2-$–Mn$^{3+}$–O$^{1-}$–Mn$^{3+}$–O$^2-$ ion chain. (b) An itinerant electron moves along the O$^2-$–Fe$^{3+}$–O$^{1-}$–Mn$^{3+}$–O$^2-$ ion chain. Here, the majority spin orientation of 3d electrons in Mn$^{3+}$ cations is up; the majority spin orientation of 3d electrons in Fe$^{3+}$ cations and O 2p electrons in O$^{1-}$ anions is down.](image1)

4.3 Resistivity ($\rho_4$) originating from scattering at the crystallite interfaces of polycrystalline samples

It is interesting to compare the resistivity of the polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ sample ($\rho_4$) prepared in this work to that of the single-crystalline La$_{0.6}$Sr$_{0.4}$Mn$O_3$ sample ($\rho_5$) reported by Urushibara et al.,$^{14}$ as shown in Fig. 8(a). We found that $\rho_4$ is 97 times (at 50 K) and 9 times (at 360 K) the value of $\rho_5$, which suggests that the resistivity ($\rho_4$) originating from scattering at the crystallite interfaces of the polycrystalline sample was far higher those originating from lattice thermal vibrating ($\rho_1$) and spin-dependent scattering ($\rho_2$). Therefore, for the polycrystalline manganites, the TCET model can be represented by the equivalent circuit shown in Fig. 4(b). Fig. 8(b) shows a comparison of $\rho_4$ with $\rho_5$, where $\rho_4$ was estimated using $\rho_4 = \rho_5 - \rho_0$.

According to the report by Urushibara et al.,$^{14}$ the temperature $T_{MI}$ for maximum resistivity is very close to the value of $T_C$ for single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ (0.175 ≤ x ≤ 0.40). However, as shown in Table 2, the values of $T_{MI}$ were distinctly lower than $T_C$ for the polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ (0.00 ≤ x ≤ 0.15) samples. This was simply due to the MI were distinctly lower than its $T_C$ (364.5 K).

4.4 Effect of crystal-cell constants on the samples’ resistivity

For the antiferromagnetic semiconductor, polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$, its resistivity was far lower than that of single-crystalline LaMnO$_3$, with a $\rho_4$/$\rho_5$ ratio of 0.51% at 270 K and 0.58% at 300 K, as shown in Fig. 8(c). A comparison of Fig. 8(a) and (c) shows an interesting phenomenon: the change in amplitude of the resistivity from that of the polycrystalline ferromagnetic conductor, La$_{0.6}$Sr$_{0.4}$MnO$_3$, to that of the
Paper

Fig. 8 (a) Temperature dependence of the resistivities, $\rho_T$ and $\rho_S$, of polycrystalline and single-crystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$ and their ratio, $\rho_T/\rho_S$. (b) Temperature dependence of the observed resistivity, $\rho_T$, and the estimated resistivity resulting from crystallite interface scattering, $\rho_{\text{pol}}$, of polycrystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$. (c) Temperature dependence of $\rho_T$ of La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ and La$_{0.6}$Sr$_{0.4}$MnO$_3$, and their ratio, $\rho_T/\rho_{\text{pol}}$. (d) Dependence of the equivalent cubic cell constant, $a_0$, of the single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ samples and the polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ samples on the doping level, $x$.

antiferromagnetic semiconductor, La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$, is far lower than the change in the amplitude of the resistivity from that of the single-crystalline ferromagnetic conductor, La$_{0.6}$Sr$_{0.4}$MnO$_3$, to that of the antiferromagnetic semiconductor, LaMnO$_3$. The primary causes of this phenomenon may be the distinct difference in the crystal-cell constants of the two systems, and the proportion of the antiferromagnetic phase. The equivalent cubic cell constants ($a_0$) of single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ (ref. 41) and polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ are shown in Fig. 8(d), which were calculated using the average volume per formula of each sample. The samples of La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{1-x}$O$_3$ (0.00 $\leq x \leq 0.3$) and La$_{1-x}$Sr$_x$MnO$_3$ (0.175 $\leq x \leq 0.40$) exhibited rhombohedral structures, while La$_{1-x}$Sr$_x$MnO$_3$ (0.00 $\leq x \leq 0.15$) was reported to have an orthorhombic structure. The value of $a_0$ of the polycrystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$ is very close to that of the single-crystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$. However, the value of $a_0$ of polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{1-x}$O$_3$ prepared in our study increased from 3.872 Å (x = 0.00) to 3.878 Å (x = 0.30), while the value of $a_0$ of single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ was reported to increase from 3.874 Å (x = 0.40) to 3.942 Å (x = 0.00). According to previous investigations, there are only Mn$^{3+}$ cations in La$_{1-x}$Sr$_x$MnO$_3$ (0.15 $\leq x \leq 0.40$). Therefore, the increase in resistivity from x = 0.40 to x = 0.15 occurred because of the increase in the crystal-cell constant, while the increase in resistivity from x = 0.15 to x = 0.00 occurred because of increases in both the crystal-cell constant and the proportion of the antiferromagnetic phase.

Obviously, an increase (in increments of 0.01 Å, for example) in $a_0$ may rapidly reduce the transition probability of the itinerant electrons whenever spin-dependent or spin-independent transitions take place, resulting in an increase in the estimated resistivity resulting from crystallite interface scattering, $\rho_{\text{pol}}$, of polycrystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$. The primary causes of this phenomenon may be the distinct difference in the crystal-cell constants of the two systems, and the proportion of the antiferromagnetic phase. The equivalent cubic cell constants ($a_0$) of single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ (ref. 41) and polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{0.7}$O$_3$ are shown in Fig. 8(d), which were calculated using the average volume per formula of each sample. The samples of La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{1-x}$O$_3$ (0.00 $\leq x \leq 0.3$) and La$_{1-x}$Sr$_x$MnO$_3$ (0.175 $\leq x \leq 0.40$) exhibited rhombohedral structures, while La$_{1-x}$Sr$_x$MnO$_3$ (0.00 $\leq x \leq 0.15$) was reported to have an orthorhombic structure. The value of $a_0$ of the polycrystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$ is very close to that of the single-crystalline La$_{0.6}$Sr$_{0.4}$MnO$_3$. However, the value of $a_0$ of polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_{0.3}$Mn$_{1-x}$O$_3$ prepared in our study increased from 3.872 Å (x = 0.00) to 3.878 Å (x = 0.30), while the value of $a_0$ of single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ was reported to increase from 3.874 Å (x = 0.40) to 3.942 Å (x = 0.00). According to previous investigations, there are only Mn$^{3+}$ cations in La$_{1-x}$Sr$_x$MnO$_3$ (0.15 $\leq x \leq 0.40$). Therefore, the increase in resistivity from x = 0.40 to x = 0.15 occurred because of the increase in the crystal-cell constant, while the increase in resistivity from x = 0.15 to x = 0.00 occurred because of increases in both the crystal-cell constant and the proportion of the antiferromagnetic phase.

Obviously, an increase (in increments of 0.01 Å, for example) in $a_0$ may rapidly reduce the transition probability of the itinerant electrons whenever spin-dependent or spin-independent transitions take place, resulting in an increase in the
samples—$\rho_0 = 0.0072$ to $1.100 \ \Omega \ \text{cm}$, $a_1 = 2.794 \times 10^{-10}$ to $1.159 \times 10^{-6} \ (\Omega \ \text{cm}) \ K^{-3}$, $T_1 = 150$ to $20 \ K$—are higher than those of the single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ samples—$\rho_0 = 0.075$ to $0.95 \ \text{m}\Omega \ \text{cm}$, $a_1 = 4.2 \times 10^{-11}$ to $2.4 \times 10^{-10} \ (\Omega \ \text{cm}) \ K^{-3}$, and $T_1 = 35$ to $10 \ K$—because of the effect of crystallite interfaces in the polycrystalline samples.

(ii) The resistivity $\rho_2$ in eqn (2) is determined by two parameters: the amplitude $a_2$; the activation energy $E_2$, which originated from spin-dependent scattering. The value of $E_2$ of the single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ samples increased from 0.515 eV ($x = 0.15$) to 0.88 eV ($x = 0.40$), which was the result of competition between two factors. One factor was the increase in the cant angle between magnetic moments of Mn$^{3+}$ cations from 0 ($x = 0.15$) to 34.9° ($x = 0.40$). Another factor was the decrease in crystal cell volume with increasing $x$. The value of $E_2$ of the polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_x$Mn$_{1-x}$O$_3$ samples increased from 0.06 eV ($x = 0.00$) to 0.12 eV ($x = 0.15$), which can be attributed to the increase in Fe-doping level because the magnetic moments of Fe$^{3+}$ cations couple antiferromagnetically with those of Mn$^{3+}$ cations. The $a_2$ values of the polycrystalline La$_{0.6}$Sr$_{0.4}$Fe$_x$Mn$_{1-x}$O$_3$ samples are far lower than those of the single-crystalline La$_{1-x}$Sr$_x$MnO$_3$ samples, possibly because of the intense scattering at the crystallite interfaces to reduce the effect of spin-dependent scattering.

5. Conclusion

In order to explain the dependence of the resistivity ($\rho$) of perovskite manganites on the test temperature ($T$), we propose a model with two channels of electrical transport (TCET): a spin-independent channel (with resistivity $\rho_s$) and a spin-dependent channel (with resistivity $\rho_d = \rho_1 + \rho_2$). At low temperature, $\rho_d$ is very high, and the electrical transport occurs along the spin-dependent channel. When $T$ is far lower than the Curie temperature ($T_C$), $\rho$ is very close to $\rho_1$, which increases with increasing $T$ owing to the thermal vibration of the crystal lattice. When $T$ is close to $T_C$, $\rho_2$ increases rapidly owing to the spin orientations of the itinerant electrons, and the local electrons of the outer O 2p and Mn 3d orbits deviating from the orientation of their ground states. Therefore, the spin-dependent electrical transport in perovskite manganites at temperatures below $T_C$ is distinctly different from the spin-independent electrical transport in metals. When $T$ is higher than $T_C$, the spin orientations of the itinerant electrons change into disorder, and electrical transport occurs along both channels, with the spin-independent transition, $\rho$, being close to $\rho_2$.

Several determining factors of the resistivity have been discussed: (i) the increase in the proportion of the antiferromagnetic phase may result in an increase in $\rho$. (ii) The resistivity $\rho_s$ originating from crystallite-interface scattering in the polycrystalline samples is far higher than $\rho_1$ and $\rho_2$ at temperatures below $T_C$. (iii) Increases in the crystal-cell constant, in increments as small as 0.01 Å, may result in rapid increases in $\rho$, which may be the reason of the high resistivity of La$_{0.85}$Sr$_{0.15}$MnO$_3$ and La$_{0.85}$Sr$_{0.15}$MnO$_3$ at low temperatures.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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