Structural, magnetic, and electrical properties of La\(_{1-x}\)Nd\(_x\)Mn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) (x ≤ 0.3)

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Abstract

We have investigated the structural, magnetic, and electrical transport properties of a series of ABO\(_3\)-type perovskite compounds, La\(_{1-x}\)Nd\(_x\)Mn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) (x ≤ 0.3). The parent compound LaMn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) is a ferromagnetic semiconductor with a Curie temperature \(T_c\) of 156 K. Upon Nd doping on La sites, the lattice parameters, unit cell volume, the B–O–B bond angle, and the B–O bond length are reduced. The Curie temperature decreases with increasing Nd content. However, Nd doping enhances the saturation magnetization at 5 K, which indicates that the Nd\(^{3+}\) moments tend to be parallel to the Mn\(^{3+/4+}\) moments at low temperature. All the samples are semiconducting throughout the temperature range studied. The resistivity can be described by the adiabatic small polaron hoping model, with an apparent reduction of polaron activation energy (\(E_a\)) below \(T_c\). In a 13 T high magnetic field, the resistivity remains semiconducting although \(E_a\) is suppressed. The effects of Nd doping in LaMn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) are discussed in terms of the smaller size and the high moment of Nd\(^{3+}\) ions.

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Keywords: Perovskite; Magnetoresistance; Small polaron

1. Introduction

Since the discovery of many interesting phenomena such as the colossal magnetoresistance (CMR) [1,2], charge ordering [3,4], orbital ordering [5,6], and phase separation [7,8] in the perovskite manganites, a great amount of effort has been devoted to understand the unusual electronic and magnetic properties of these materials. The basic structural, magnetic, and transport properties of R\(_{1-x}\)A\(_x\)MnO\(_3\), where R is a trivalent lanthanide cation and A is a divalent (e.g. alkaline earth) ion, have been widely studied in the past years. The parent compound LaMnO\(_3\) is an antiferromagnetic insulator. The doping on La sites with divalent cations results in a Mn\(^{3+/4+}\) mixed-valence state, which creates mobile charge carriers and ferromagnetic ordering of Mn spins [9]. The magnetic and electrical properties of these compounds have been traditionally explained in terms of the double-exchange (DE) mechanism in which the motion of \(e_g\) electron between the two partially filled d shells with strong on-site Hund’s coupling results in the magnetic coupling between Mn\(^{3+}\) and Mn\(^{4+}\) ions [10]. However, recent detailed research has shown that double-exchange alone is insufficient to account for the rich variety of phenomena found in these compounds. Other factors, particularly the strong electron–phonon coupling due to the local Jahn–Teller (JT) distortion of Mn\(^{3+}\) ion [11] as well as lattice strain and deformations that affect the Mn\(^{3+}\)–O–Mn\(^{4+}\) bond angle and Mn–O bond length [12,13], were proposed to play a key role in these compounds. It has been generally recognized that the system involves complex interplays among charge, lattice, and spin.

As mentioned above, the ferromagnetism in perovskite manganites is usually generated by doping on La sites with a divalent ion. However, in some cases ferromagnetism can
be produced without La-site doping. A good example is the LaMn$_{1-x}$Cr$_3$O$_7$ system. Sun et al. [14] demonstrated that a ferromagnetic ordering develops when the Mn$^{3+}$ ions in LaMnO$_3$ are partially substituted by Cr$^{3+}$ ions which have the same electronic configuration as Mn$^{4+}$ ($t_{2g}$). The origin of the ferromagnetic ordering in LaMn$_{1-x}$Cr$_3$O$_7$ is still controversial, i.e., whether it is due to the double-exchange or superexchange (SE) interaction [14–16]. Moreover, Cr doping introduces strong ferromagnetic ordering but does not significantly promote the motion of electrons. As a result, LaMn$_{1-x}$Cr$_3$O$_7$ becomes a ferromagnetic semiconductor at low temperature [14].

In the La$_{1-x}$A$_x$MnO$_3$ mixed-valence manganite, replacing La with smaller lanthanide element, such as Nd, can result in the distorted perovskite structure with three-dimensional networks of the MnO$_6$ octahedra. Decrease of the average ionic radius $r_A$ of the A site reduces the one-electron bandwidth $W$ of the $e_g$ band via variation of the Mn–O–Mn bond angle and Mn–O bond length. Therefore, the magnetic and electric properties are strongly affected by Nd doping. For example, Cherif et al. [17] found that there is a structure transition (from rhombohedral to orthorhombic structure) in (La$_{1-x}$Nd$_x$)$_{0.7}$Sr$_{0.3}$MnO$_3$ due to the substitution of La$^{3+}$ by Nd$^{3+}$ and $T_C$ decreases with the increasing of Nd content. Moritomo et al. [18] also reported the lattice effect on the anisotropic magnetic and transport properties in single crystals of (La$_{1-x}$Nd$_x$)$_{0.7}$Sr$_{0.3}$MnO$_3$. Meanwhile, Nd$^{3+}$ ions, unlike La$^{3+}$ ions, have an intrinsic magnetic moment. The Nd$^{3+}$ magnetic moments in it can be either parallel or antiparallel to the moments of the Mn$^{3+}$/Mn$^{4+}$ ions [19]. Therefore, it would be worthwhile to investigate the effects of Nd substitution in the ferromagnetic semiconductor LaMn$_{1-x}$Cr$_3$O$_7$, which has not yet been studied to our knowledge. In this work, we have synthesized a series of La$_{1-x}$Nd$_x$Mn$_{0.8}$Cr$_{0.2}$O$_3$ sample and investigated the structural, magnetic, and electrical properties in details.

2. Experiments

Polycrystalline samples of La$_{1-x}$Nd$_x$Mn$_{0.8}$Cr$_{0.2}$O$_3$ ($x = 0.0, 0.05, 0.1, 0.2$, and $0.3$) were synthesized by the conventional solid-state reaction method. Raw materials of La$_2$O$_3$, Nd$_2$O$_3$, MnCO$_3$, and Cr$_2$O$_3$ with purities higher than 99.9% were weighed in stoichiometric amounts, then mixed and prefired at 1173 K for 24 h. After grinding, the ball-milled powder was pressed into pellets and sintered in air at 1523 K for 24 h. This process was repeated several times until single-phased samples were obtained. The phase purity and the crystal structure of these samples were examined by powder X-ray diffraction (XRD) at room temperature using a Rigaku X-ray diffractometer. The XRD measurements were performed with a step of 0.02° and a speed of 10°/s. The magnetic measurements were performed by using a superconducting quantum interface device magnetometer (Quantum Design PPMS-7). The resistivity measurements were carried out using the standard four-point technique in a commercial physical properties measurement system (Quantum Design PPMS-14).

3. Results and discussion

3.1. Structural analysis

Fig. 1 shows the XRD patterns of several representative samples ($x = 0.0, 0.1$, and $0.3$). For comparison, the refining results using the Rietveld method [20] are also plotted in Fig. 1. Rietveld refinement is a technique devised by Hugo Rietveld for use in the characterization of crystalline materials. The Rietveld method uses a least squares approach to refine a theoretical line profile until it matches the measured profile. The introduction of this technique was a significant step forward in the diffraction analysis of powder samples as it was able to deal reliably with strongly overlapping reflections. The diffraction peaks are sharp, indicating the good quality of the forming phase. As is shown in Fig. 1, all the patterns can be well indexed on an orthorhombic (Pbnm) perovskite structure and no trace of secondary phase was detectable. We also tried to synthesize La$_{1-x}$Nd$_x$Mn$_{0.8}$Cr$_{0.2}$O$_3$ samples with $x \geq 0.4$. However, no single-phased sample could be obtained after using various sintering conditions.

The crystallographic data of La$_{1-x}$Nd$_x$Mn$_{0.8}$Cr$_{0.2}$O$_3$ ($x \leq 0.3$) were listed in Table 1. Due to the smaller ionic radius of Nd$^{3+}$ (1.41 Å) compared to that of La$^{3+}$ (1.50 Å) [21], the lattice parameters of these samples decrease with increasing Nd content. The lattice constant $a$ decreases by 0.67% from 5.568(2) Å for $x = 0.0$ to 5.530(7) Å for $x = 0.3$.

![Fig. 1. XRD patterns of La$_{1-x}$Nd$_x$Mn$_{0.8}$Cr$_{0.2}$O$_3$ ($x = 0.0, 0.1$, and $0.3$). The observed and calculated patterns using the Rietveld method are shown as the + markers and the top solid line, respectively. The vertical markers stand for the angles of Bragg reflections. The lowest solid line represents the difference between the calculated and observed intensities. The observed and calculated patterns using the Rietveld method are shown as the + markers and the top solid line, respectively. The vertical markers stand for the angles of Bragg reflections. The lowest solid line represents the difference between the calculated and observed intensities. When $x = 0.0$, $R_p$ (%) = 5.895, $R_{wp}$ (%) = 7.064, $\chi^2 = 1.943$. When $x = 0.1$, $R_p$ (%) = 8.454, $R_{wp}$ (%) = 10.226, $\chi^2 = 2.009$. For $x = 0.3$, $R_p$ (%) = 8.974, $R_{wp}$ (%) = 10.069, $\chi^2 = 2.095$.](image-url)


Table 1

<table>
<thead>
<tr>
<th>x</th>
<th>0.0</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Ortho</td>
<td>Ortho</td>
<td>Ortho</td>
<td>Ortho</td>
<td>Ortho</td>
</tr>
<tr>
<td>a (Å)</td>
<td>5.568(2)</td>
<td>5.560(3)</td>
<td>5.553(3)</td>
<td>5.542(9)</td>
<td>5.530(7)</td>
</tr>
<tr>
<td>b/√2 (Å)</td>
<td>5.516(6)</td>
<td>5.514(6)</td>
<td>5.507(2)</td>
<td>5.499(9)</td>
<td>5.494(2)</td>
</tr>
<tr>
<td>c (Å)</td>
<td>5.536(8)</td>
<td>5.531(1)</td>
<td>5.522(2)</td>
<td>5.510(4)</td>
<td>5.498(6)</td>
</tr>
<tr>
<td>Unit cell volume (Å³)</td>
<td>240.523(4)</td>
<td>239.8488</td>
<td>238.8394</td>
<td>237.5712</td>
<td>236.2913</td>
</tr>
<tr>
<td>( \delta_{B-OI} ) (Å)</td>
<td>1.979(2)</td>
<td>1.973(4)</td>
<td>1.970(1)</td>
<td>1.968(4)</td>
<td>1.962(5)</td>
</tr>
<tr>
<td>( \delta_{B-OII} ) (Å)</td>
<td>1.984(8)</td>
<td>1.980(3)</td>
<td>1.973(9)</td>
<td>1.970(1)</td>
<td>1.965(4)</td>
</tr>
<tr>
<td>( \theta(B-OI-B) )</td>
<td>172.2(1)</td>
<td>171.7(5)</td>
<td>170.9(9)</td>
<td>169.7(6)</td>
<td>168.5(4)</td>
</tr>
<tr>
<td>( \theta(B-OII-B) )</td>
<td>174.5(4)</td>
<td>173.9(5)</td>
<td>173.2(9)</td>
<td>171.7(7)</td>
<td>170.9(4)</td>
</tr>
</tbody>
</table>

x = 0.3, indicating significant reduction of the B–B distance with x. Similarly, the reducing ratios of lattice constant b and c are 0.41% and 0.69%, respectively. Consequently, the unit cell volume decreases with increasing x. For example, when x = 0.0, the unit cell volume is 240.523(4) Å³ and it reduces to 236.291(3) Å³ for x = 0.3, reaching to 1.79% of the reducing ratio. The variation of lattice parameters and the unit cell volumes as a function of x are shown in Fig. 2.

In the orthorhombic structure, there are two different oxygen sites, i.e., the out-plane \( O_I \) and the planar \( O_P \). As listed in Table 1, the bond angles of B–O–I–B and B–OII–B decrease with the increasing of Nd content. In the perovskite LaMnO₃ the manganese ions are surrounded by regular octahedra of oxygens. The octahedra of MnO₆ are linked together by their corners to form a three-dimensional framework, while the La ions occupy the A site between these octahedra. The tolerance factor \( t \), defined as \( t = (A-O)/\sqrt{2}(B-O) \), where \( A-O \) and \( B-O \) are the mean cation–oxygen bond length of A site and B site, respectively, reflects the local microscopic distortions from the ideal perovskite structure (\( t_1 \)). With decreasing temperature, all samples exhibit a magnetic transition from a paramagnetic (PM) to a ferromagnetic (FM) state. The Curie temperature, \( T_c \), defined as the minimum in the \( dM/dT \) curve, is 156, 151, 147, 145, and 127 K for \( x = 0.0, 0.05, 0.1, 0.2, \) and 0.3, respectively. Apparently, with increasing Nd content the paramagnetic–ferromagnetic transition is broadened and shifts to lower temperatures. Meanwhile, for all samples, both ZFC and FC magnetization show a drop at low temperature, which seems to indicate that there could be a competing AFM component.

3.2. Magnetic properties

Previous studies [14,15] have demonstrated that LaMn₁₋ₓCrₓO₃ exhibits strong ferromagnetism although both of the parent compounds, LaMnO₃ and LaCrO₃, are antiferromagnetic. Especially, when the Cr content \( x \) is 0.2, LaMn₁₋ₓCrₓO₃ exhibits a high \( T_c \). Fig. 3(a)–(d) presents the magnetization of La₁₋ₓNdₓMn₀.₈Cr₀.₂O₃ \( \leq 0.3 \) as a function of temperature in a 50 Oe magnetic field with both the zero-field-cooled (ZFC) and field-cooled (FC) processes. With decreasing temperature, all samples exhibit a magnetic transition from a paramagnetic (PM) to a ferromagnetic (FM) state. The Curie temperature, \( T_c \), defined as the minimum in the \( dM/dT \) curve, is 156, 151, 147, 145, and 127 K for \( x = 0.0, 0.05, 0.1, 0.2, \) and 0.3, respectively. Apparently, with increasing Nd content the paramagnetic–ferromagnetic transition is broadened and shifts to lower temperatures. Meanwhile, for all samples, both ZFC and FC magnetization show a drop at low temperature, which seems to indicate that there could be a competing AFM component.

Cr-doping on the Mn-site enhances the ferromagnetic interaction in LaMnO₃, which suggests that a ferromagnetic exchange interaction occurs between Mn and Cr. However, the sample shows double-step dropping feature below \( T_c \), which is caused by the coexistence of competing FM and AFM interaction. Substitution of Cr in place of Mn gives rise to a FM interaction through Mn³⁺–O–Cr³⁺ as well as an AFM interaction through Cr³⁺–O–Cr³⁺.
Adding the AFM exchange coupling of Mn\(^{3+}\)--O--Mn\(^{3+}\), the double-step dropping of the magnetization may be explained by the fact that the two AFM interactions (Mn\(^{3+}\)--O--Mn\(^{3+}\) and Cr\(^{3+}\)--O--Cr\(^{3+}\)) have different coupling constants [14]. As we know, the coexistence and competition between ferromagnetic and antiferromagnetic interaction could lead to the formation of a cluster glass state. As Fig. 3 illustrates, there is a big divergence between ZFC and FC magnetization below \(T_c\), which is a characteristic of cluster glass that has no simple long-range ferromagnetic order. When Nd is doped in LaMn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) on the La site, the Curie temperature, \(T_c\), decreases. As shown in Fig. 3(a)-(d), \(T_c\) of La\(_{0.95}\)Nd\(_{0.05}\)Mn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) is 151 K, but \(T_c\) decreases to 127 K for \(x = 0.3\). The \(T_c\) variation has been interpreted by the decrease of B–O–B bond angles and B–O bond length as Nd content increases. In fact, the substitution of La by Nd should not change the Mn\(^{3+}\)/Cr\(^{3+}\) ratio, but the difference in ionic size affects the B–O–B bond angle (chemical pressure effect), and the bandwidth (\(e_g\)) was narrowed, resulting in a gradual enhancement of the effective band gap. Consequently, the transfer interaction of \(e_g\) electrons from Mn\(^{3+}\) to Cr\(^{3+}\) should be reduced. The variation of the Curie temperature \(T_c\) in the series of La\(_{1-x}\)Nd\(_x\)Mn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) (\(x \leq 0.3\)) is similar to that observed in mixed-valence manganites (La\(_{1-x}\)Nd\(_x\)Mn\(_{1-y}\)Co\(_y\)O\(_3\)) [17] and (La\(_{1-x}\)Nd\(_x\)La\(_{1-y}\)Sr\(_y\)Mn\(_2\)O\(_7\)) [18]. This may indicate that the Mn\(^{3+}\)--O--Cr\(^{3+}\) exchange interaction in LaMn\(_{0.8}\)Cr\(_{0.2}\)O\(_3\) is similar to the Mn\(^{3+}\)--O--Mn\(^{4+}\) double-exchange interaction.

The low-field (50 Oe) magnetization above \(T_c\) for \(x = 0.0\) and 0.3 samples are fitted to a Curie–Weiss law \(M = \chi_{\text{eff}}/H\) \((T - T_\theta)\), where \(M/H\) is the DC susceptibility, \(\chi_{\text{eff}}\) is the effective paramagnetic moment and \(T_\theta\) is the Curie–Weiss temperature. The range of fitting temperature is from 230 to 275 K for \(x = 0.0\) and from 200 to 275 K for \(x = 0.3\), in which the sample is in the pure

![Fig. 3](image-url)
The obtained \( \mu_{\text{eff}} \) and \( T_\Theta \) are 5.475\( \mu_B \) and 5.735\( \mu_B \), 157.5 and 128.4 K for \( x = 0.0 \) and 0.3 samples, respectively. The positive values of the Curie–Weiss temperature indicate the ferromagnetic interaction between spins.

In order to identify the magnetic structure below \( T_c \), we also measured the \( M–H \) curves at 5 and 50 K as shown in the insets of Fig. 3. For all samples, the magnetization increases rapidly at low field and approaches to saturation at high field. Moreover, the magnetization hysteresis is very small and the difference of \( M–H \) curves between 5 and 50 K is slight. All these features are characteristics of a soft ferromagnet. These results seem contradictory to the existence of cluster glass phase as indicated by the low-field \( M(T) \) curves. In fact, the \( M(T) \) curve measured in 1000 Oe does not show the drop at low temperature [16]. Therefore, the cluster glass component, if does exist, is not dominating so that a moderate field can destroy it. The saturation magnetization (\( M_s \)) at 5 K, as deduced from the extrapolation of \( M–1/H \) curve, is 59.58 emu/g for \( x = 0.3 \). With increase of the Nd content, \( M_s \) increases and reaches 65.4 emu/g for \( x = 0.3 \). This indicates that the moment of Nd\(^{3+} \) ions tends to align parallel to Mn\(^{3+}/Cr^{3+} \) moments at low temperature.

### 3.3 Electrical transport properties

In Fig. 4, we show the temperature dependence of resistivity of \( \text{La}_{1-x}\text{Nd}_x\text{Mn}_{0.8}\text{Cr}_{0.2}\text{O}_3 \) samples in 0 and 13 T field. Although they show good ferromagnetism, all
samples are semiconducting in the whole temperature range studied. The resistivity increases with the increasing the Nd, which is similar to the results observed in \( \text{La}_{1-x}\text{Nd}_x\text{Sr}_{0.3}\text{MnO}_3 (0 \leq x \leq 1) \) [17]. This also indicates that the \( \text{Mn}^{3+}-\text{O}-\text{Cr}^{3+} \) exchange interaction is similar to the \( \text{Mn}^{3+}-\text{O}-\text{Mn}^{4+} \) double-exchange interaction. From above analysis we know that the replacement of \( \text{La}^{3+} \) ions by a smaller radius \( \text{Nd}^{3+} \) ions in \( \text{La}_{1-x}\text{Nd}_x\text{Mn}_{0.8}\text{Cr}_{0.2}\text{O}_3 \) series causes a large distortion of the B–O–B bond, which weakens the exchange action and reduces the transfer of the \( e_g \) electrons. An applied magnetic field (13 T) significantly decreases the resistivity in \( \text{La}_{1-x}\text{Nd}_x\text{Mn}_{0.8}\text{Cr}_{0.2}\text{O}_3 \) \( (x \leq 0.3) \), as shown in Fig. 4. Under an applied magnetic field, the orientation of random ferromagnetic clusters is forced to align uniformly so that the degree of spatial magnetic disorder is reduced, which favors the electron delocalization and consequently results in a distinct drop of resistivity.

The magnetoresistance (MR) is plotted in the insets of Fig. 4, where MR is defined by \( MR = \rho(0 \text{T}) - \rho(13 \text{T}) / \rho(13 \text{T}) \). The MR exhibits two peaks, especially for doping level \( x = 0.05, 0.1, \) and \( 0.3 \). The first peak of MR lies near \( T_c \), which suggests that it could originate from the mechanism based on the double-exchange between Mn and Cr ions. Meanwhile, in \( \text{La}_{1-x}\text{Nd}_x\text{Mn}_{0.8}\text{Cr}_{0.2}\text{O}_3 \) series, as above discussed, there exists AFM interaction through \( \text{Cr}^{3+}-\text{O}-\text{Cr}^{3+} \) and \( \text{Mn}^{3+}-\text{O}-\text{Mn}^{3+} \). The complex of ferromagnetic and antiferromagnetic interaction, adding the lattice distortion due to the Nd doping, would favor the formation of ferromagnetic cluster rather than long-range ferromagnetic domains. Due to the randomly distributed moment of FM clusters and the large spin fluctuation, there should be severe spatial magnetic disorder which may play a key role in electron localization. The competition between carrier localization by magnetic disorder and carrier delocalization by double-exchange below \( T_c \) may lead to two peaks of MR.

Previous transport measurements have indicated that the resistivity of \( \text{LaMn}_{1-x}\text{Cr}_x\text{O}_3 \) in semiconducting regime could be described by the Emin–Holstein theory of adiabatic small polaron model [23], \( \rho = B T \exp(E_a/k_B T) \), where \( B \) is a constant, \( E_a \) is the resistivity activation energy, and \( k_B \) is Boltzmann constant, across the entire doping range [14]. Therefore, we used the small polaron model to fit the resistivity of \( \text{La}_{1-x}\text{Nd}_x\text{Mn}_{0.8}\text{Cr}_{0.2}\text{O}_3 \). As shown in Fig. 5, the resistivity of our samples can be fitted by the adiabatic small polaron model both above and below the magnetic ordering temperature \( T_c \), with an apparent change in the slope of resistivity near \( T_c \). This slope change indicates that there exists a close correlation between magnetic state and transport behavior. From the fits, we obtained the polaron activation energy \( E_a \) as summarized in Table 2. From Table 2, it is clear that the values of \( E_a \) in the ferromagnetic states are distinctly lower than those in the paramagnetic states, which indicates that the onset of ferromagnetic ordering promotes the transfer of charge carrier. This is a characteristic of double-exchange interaction.

### Table 2

<table>
<thead>
<tr>
<th>0T</th>
<th>13T</th>
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<tr>
<td>( E_a ) (meV)</td>
<td>( E_a' ) (meV)</td>
</tr>
<tr>
<td>( T &gt; T_c )</td>
<td>( T &lt; T_c )</td>
</tr>
<tr>
<td>( x = 0.0 )</td>
<td>186</td>
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<tr>
<td>( x = 0.05 )</td>
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<td>( x = 0.1 )</td>
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<td>( x = 0.2 )</td>
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<tr>
<td>( x = 0.3 )</td>
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### 4. Summary

In summary, we have investigated the effect of Nd doping in \( \text{LaMn}_{0.8}\text{Cr}_{0.2}\text{O}_3 \) on the structural, magnetic, and electrical properties. The lattice parameters, unit cell
volume, the B–O–B bond angle, and the B–O bond length decrease with increasing Nd content. The Curie temperature $T_c$ is reduced by Nd doping, but the saturation magnetization at low temperature is enhanced, which suggests that Nd$^{3+}$ moments tend to align parallel to Mn$^{3+}$/Cr$^{3+}$ moments at low temperature. Although La$_{1-x}$Nd$_x$Mn$_{0.8}$Cr$_{0.2}$O$_3$ samples exhibit strong ferromagnetism at low temperature, the resistivity of them remains semiconducting in the whole temperature ranged studied. The resistivity can be described by the adiabatic small polaron hoping model, with a change of polaron activation energy below $T_c$. In a magnetic field, the polaron activation energy is reduced so that the electron transfer is enhanced, which leads to a large MR effect. The effects of Nd doping in LaMn$_{0.8}$Cr$_{0.2}$O$_3$ are similar to those observed in mixed-valence manganite, which may indicate that the Mn$^{3+}$–O–Cr$^{3+}$ exchange interaction is similar to the Mn$^{3+}$–O–Mn$^{4+}$ double exchange interaction.

Acknowledgments

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