Comparison of the Giant Magnetoimpedance Effect between Ferromagnetic \( \text{La}_{0.64}\text{Ba}_{0.36}\text{MnO}_{3-\delta} \) and Paramagnetic \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{0.95}\text{Fe}_{0.05}\text{O}_{3-\delta} \)

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In the present paper, ac electric transport behavior of \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) with \( x = 0 \) (the ferromagnetic phase) and \( x = 0.05 \) (the paramagnetic phase) are comparatively investigated at a temperature of 300K. The reactance X is positive for the \( x = 0 \) but negative for the \( x = 0.05 \). For \( x = 0 \), the impedance Z increases at first, undergoes a peak and a valley, and finally increases again with increasing ac frequency. On the contrary, for \( x = 0.05 \), the impedance decreases monotonically with increasing ac frequency. Meanwhile, the giant magnetoimpedance effect has been found in both ferromagnetic \( x = 0 \) and paramagnetic \( x = 0.05 \) at 300K. Results also show that with increasing frequency the change ratio of the magnetoimpedance \( (Z(0) - Z(5172A^{-1})) / Z(0) \) increases for the sample \( x = 0 \) but decreases for the sample \( x = 0.05 \).

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1. Introduction

Recently the perovskite manganites \( \text{La}_{1-x}\text{A}_x\text{MnO}_3 \) (A=Ca, Sr, Ba) have attracted great attention due to the dc colossal magnetoresistance effect (CMR) which is of potential applications in magnetic sensing and recording. 1-5 A transition from a paramagnetic semiconductor or insulator to a ferromagnetic metal occurs near Curie temperature \( T_C \). Application of an external magnetic field of several teslas suppresses the resistance much. Recently, the giant magnetoimpedance effect of La–Ba–Mn–O oxides has been observed. 6,7 In the present work, comparison of the ac electric transport and giant magnetoimpedance effects under low dc magnetic fields \( H \leq 5.172 \text{kA/m}^{-1} \) in sintered \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) with \( x = 0 \) (ferromagnetic phase) and with \( x = 0.05 \) (paramagnetic phase) at 300K were performed.

2. Experiments

The sintered samples \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) (\( x = 0, 0.05, 0.1 \)) were prepared using solid state reaction method. X-ray diffraction analysis indicated that they are of single phase with perovskite structure. The thermal magnetic curves of sintered samples \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) were measured with vibrating sample magnetometer (VSM) under 47.746 kA m\(^{-1}\) for determining Curie temperatures. The magnetoimpedance measurements were carried out using a HP4192A impedance analyzer at 300K. The sample was connected to the analyzer with the accessory 16048 test lead which was carefully designed and contains four cables. The cables were 100 cm long and permitted the sample to sit within a Helmholtz coil (diameter 30 cm), which produce a dc magnetic field \( H < 5.570 \text{kA/m}^{-1} \). The coils were so placed that the applied field was perpendicular to the Earth’s magnetic field. The sample was connected to the analyzer with four coaxial cables. The measurement of the magnetoimpedance \( Z \) was carried out with an ac current in the direction parallel to the dc magnetic field. In order to provide more information, the magnetoresistance \( R \) and magnetoresistance \( X \) were also measured using a HP4192A impedance analyzer at 300K.

3. Results and Discussion

The Fe content dependence of Curie temperature for \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) is shown in Fig. 1. It can be seen that the Curie temperatures are 325, 285 and 230K for sintered samples \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) with \( x = 0.0, 0.05, 0.1 \), respectively. That means that at 300K the sample \( x = 0 \) is ferromagnetic metal, but samples \( x = 0.05 \) and 0.1 are paramagnetic semiconductors or insulators.

![Fe content dependence of Curie temperature for La0.64Ba0.36Mn3-δFeO3-δ.](image)

The ac frequency \( f \) dependences of the impedance \( Z \), resistance \( R \) and reactance \( X \) at the absence of the magnetic field \( (H = 0) \) for sintered samples \( \text{La}_{0.64}\text{Ba}_{0.36}\text{Mn}_{1-x}\text{Fe}_x\text{O}_{3-\delta} \) (\( x = 0 \) and 0.05) at 300K were plotted in Fig. 2. For \( \text{La}_{0.64}\text{Ba}_{0.36}\text{MnO}_{3-\delta} \) (\( x = 0 \)), with in-
Fig. 2 The ac frequency dependences of the impedance $Z$, resistance $R$ and reactance $X$ at the absence of the magnetic field $H = 0$ for the samples $La_{0.64}Ba_{0.36}Mn_{1-x}Fe_{0.05}O_3$ ($x = 0.05, 0.05$).

Increasing frequency, the impedance $Z$ increases at first, undergoes a small peak at about 0.8 MHz, drops to a small valley at about 1.4 MHz, and finally increases again with increasing frequency. Similar frequency dependence was also found for the case of resistance $R$. However, the peak and the valley for resistance $R$ occurs at 0.9 and 1.5 MHz, respectively. The increase of impedance and reactance with frequency is mainly due to the skin effect of the metallic state of the $La_{0.64}Ba_{0.36}MnO_3$ ($x = 0$) below Curie temperature. The reactance $X$ is positive showing that the sample is mainly controlled by the inductive-like behavior. Different from a simple inductive material whose inductive component $X = 2\pi fL$ increases with increasing frequency $f$ ($f = \omega / 2\pi$), there are two peaks and two valleys for $X$ in the frequency range of 0.1 MHz $< f < 12$ MHz. The sharp peak and valley located at 0.6 and 1.0 MHz, respectively. The broad peak and valley occurs at 3 and 6 MHz. On the contrary, for the sample $La_{0.64}Ba_{0.36}Mn_{0.05}Fe_{0.05}O_3$ ($x = 0.05$) at 300 K above Curie temperature, both the impedance $Z$ and resistance $R$ decrease monotonically with increasing frequency from 0.1 to 12 MHz. The reactance $X$ of the $x = 0.05$ is negative. This shows that the sample $x = 0.05$ is mainly controlled by the capacitance-like behavior. Different from a capacitance material whose absolute value of $X = -1/2\pi fC$ decreases with increasing frequency $f$, the absolute value of $X$ for $La_{0.64}Ba_{0.36}Mn_{0.05}Fe_{0.05}O_3$ ($x = 0.05$) increases with increasing frequency $f$ evidently at low frequency, then undergoes a maximum and finally decreases.

The dc magnetic field dependence of the ratio of magneto-impedance $(Z(H) - Z(0))/Z(0)$ for $x = 0$ at 12 MHz and for $x = 0.05$ at 0.5 MHz at 300 K are shown in Fig. 3 and Fig. 4, respectively. Giant magnetoimpedance effects can be observed for samples $x = 0$ and $x = 0.05$. The value of $(Z(H) - Z(0))/Z(0)$ is $-1.08\%$ for sample $x = 0$ at 12 MHz and is $-1.4\%$ for sample $x = 0.05$ at 0.5 MHz when a magnetic field $H$ is 5.172 kA/m. According to the classical electrodynamics, the surface impedance of the conductor can be expressed as $\zeta = \zeta' + i\zeta'' = \sqrt{\mu / \varepsilon}$, where $\mu$ is the magnetic permeability, $\varepsilon$ is the permittivity. In the frequency range where $\varepsilon$ can be expressed in terms of the ordinary conductivity $\sigma$, one has the surface impedance of the conductor as $\zeta = (1 - i) \sqrt{\frac{\mu_0}{\varepsilon_0}}$. This implies that the surface impedance of materials depends strongly on the magnetic permeability. Further more, for the case of the metallic flake or film with 2a depth, the impedance can be described as $Z = R_{dc}$, where $k = (1 + i) / \delta_m$, the penetration depth $\delta_m = \frac{c}{2\pi\sigma \mu_0}$, $c$ is the light velocity in the vacuum.
When a dc magnetic field is applied on the perovskite sample with the wake, the magnetic field may influence the transverse permeability $\mu_p$, and thus changes the impedance of the sample. The detailed calculations on GMI for perovskite oxides are in progress and the results will appear in a separated paper soon.

The ac frequency $f$ dependence of the ratios of the magnetoimpedance $(Z(0) - Z/(5172 A \cdot m^{-1}))/Z(0)$ for samples $La_{0.64}Ba_{0.36}MnO_3\ldots (x = 0)$ and $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots (x = 0.05)$ at 300 K are shown in Fig. 5. For ferromagnetic $La_{0.64}Ba_{0.36}MnO_3\ldots (x = 0)$, the ratio $(Z(0) - Z/(5172 A \cdot m^{-1}))/Z(0)$ increases from 0.31 to 1.08% with increasing frequency $f$ from 5 to 12 MHz. Below frequency 5 MHz, the value is very small. In contrast, for paramagnetic $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots (x = 0.05)$, it decreases from 1.86% to zero with increasing frequency $f$ from 0.1 to 12 MHz.

In order to provide more useful information, behavior of the magnetoimpedance and magnetoresistance of sintered samples $La_{0.64}Ba_{0.36}Mn_{1-x}Fe_xO_3\ldots (x = 0$ and 0.05) were also investigated. Figure 6 shows the frequency $f$ dependence of the ratios of magnetoresistance $(R(0) - R/(5172 A \cdot m^{-1}))/R(0)$ for samples $La_{0.64}Ba_{0.36}MnO_3\ldots (x = 0)$ and $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots (x = 0.05)$ at 300 K, respectively. The magnetoresistance ratio of sample $x = 0$ increases from 0.25% to 0.95% with increasing frequency from 5 to 12 MHz. However, for sample $x = 0.05$, the magnetoresistance ratio decreases from 1.75 to $-1.22\%$ with increasing frequency from 0.1 to 5 MHz, and with further increase of frequency there is an increase of ratio $(R(0) - R/(5172 A \cdot m^{-1}))/R(0)$. The frequency $f$ dependence of the change ratios of magnetoreactance $(X(0) - X/(5172 A \cdot m^{-1}))/X(0)$ for samples $La_{0.64}Ba_{0.36}MnO_3\ldots (x = 0)$ and $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots (x = 0.05)$ at 300 K is shown in Fig. 7. The magnetoreactance ratio for sample $x = 0$ increases with increasing frequency, and the value of magnetoreactance ratio is 2.99% at 12 MHz. In contrast, the magnetoreactance ratio for sample $x = 0.05$ decreases from 2.32% to zero with increasing frequency from 0.1 to 12 MHz.

In conclusion, in the present work, comparison of the giant magnetoimpedance effect between ferromagnetic $La_{0.64}Ba_{0.36}MnO_3\ldots$ and paramagnetic $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots$ has been performed. The ferromagnetic phase $La_{0.64}Ba_{0.36}MnO_3\ldots$ ($x = 0$) at 300 K below Curie temperature has positive reactance controlled by the inductive-like behavior. On the contrary, the paramagnetic $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots$ ($x = 0.05$) at 300 K above Curie temperature has negative reactance dominated by the capacitance-like behavior. However, they have some special characters in the frequency dependence of reactance $X$, such as the peak and valley for $x = 0$, and the increase of $X$ at low frequency for $x = 0.05$. Besides of the dc colossal magnetoresistance CMR effect in perovskite oxides, the giant magnetoimpedance GMI effect under low dc magnetic field has been found in both the ferromagnetic phase $La_{0.64}Ba_{0.36}MnO_3\ldots$ and the paramagnetic phase $La_{0.64}Ba_{0.36}Mn_{0.95}Fe_{0.05}O_3\ldots$. The GMI effect found in perovskite oxides may be explained in the framework of the classical electrodynamics. CMR effect needs large field such as several teslas in general (for example, $(R(0) - R(H))/R(0) = 2-3\%$ at about $H = 1T = 10^7/4\pi$ A-m$^{-1}$ for La–Sr–Mn–O at room tempera-
In the present work, \((Z(0)-Z(H))/Z(0) = 1\text{--}2\%\) at \(H = 5.172 \text{kA m}^{-1}\) in \(La_{0.64}Ba_{0.36}\text{MnO}_{3-\delta}\) can be obtained in GMI effect. Such low field GMI effect may be of special interest in magnetic sensing and recording. Our experimental results also indicate that a large magnetore impedance change appears at higher frequency (such as 12 MHz) for ferromagnetic phase \(La_{0.64}Ba_{0.36}\text{MnO}_{3-\delta}\) but at lower frequency (such as 0.1 MHz) for the paramagnetic phase \(La_{0.64}Ba_{0.36}\text{Mn}_{0.95}\text{Fe}_{0.05}\text{O}_{3-\delta}\), which should be considered when the perovskite oxides are used in the practical electronic circuits in future.

REFERENCES