Hall Resistivity in Ferromagnetic Manganese-Oxide Compounds

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Abstract

Temperature-dependence and magnetic field-dependence of the Hall effect and the magnetic property in manganese-oxide thin films are studied. The spontaneous magnetization and the Hall resistivity are obtained for a various of magnetic fields over all the temperature. It is shown that the Hall resistivity in small magnetic field is to exhibit maximum near the Curie point, and strong magnetic field moves the position of the Hall resistivity peak to much high temperature and suppresses the peak value. The change of the Hall resistance in strong magnetic field may be larger than that of the diagonal ones. The abnormal Hall resistivity in the ferromagnetic manganese-oxide thin-films is attributed to the spin-correlation fluctuation scattering.

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I. INTRODUCTION

Recently colossal negative magnetoresistance (MR) effect has been found in ferromagnetic perovskite-like La$_{1-x}$R$_x$MnO$_3$ and Nd$_{1-x}$R$_x$MnO$_3$ (R = Ba, Sr, Ca, Pb, etc.) [1 - 4] thin films. In epitaxial La$_{1-x}$Ca$_x$MnO$_3$ and Nd$_{1-x}$Sr$_x$MnO$_3$ thin films, the resistivity in applied magnetic field decreases several order in magnitude under strong magnetic field, which is much larger than that found in ferromagnetic/nonmagnetic metallic multilayers. Since such a huge MR change has potential application for magnetic sensor, magnetic recording and many other aspects, it also presents another possible MR mechanism which is different from that in magnetic multilayer, it arises extensive attention and interests in the past two years [5 - 12].

Undoped LaMnO$_3$ is an antiferromagnetic insulator [13 - 16], its magnetic structure and magnetic properties had been studied in the early of 1950’s. After the substitution of a part of trivalent La or Nd ions by Ca, Sr, Pb, Ba or other divalent elements, Mn$^{+3}$ and Mn$^{+4}$ ions coexist, the valence fluctuation between them is thus assumed to be important and may contribute to the hopping conductivity and other transport properties. In the substitution of La or Nd ions, La$_{1-x}$R$_x$MnO$_3$ and Nd$_{1-x}$R$_x$MnO$_3$ systems may occur the metal-insulator transition, the electronic states in doped systems at the edge of metal-insulator transition can be heavily affected by the long-range magnetic order and the external magnetic field. Some mechanism have been proposed to explain the colossal MR effect in these systems [8 - 11]. The magnetic polaron mechanism [1 - 3], the spin disorder scattering [8, 9] and the metal-insulator transition [11] induced by the magnetic field seem to be difficult to explain the colossal MR behavior in strong magnetic field over all the temperature satisfactorily.
In recent study [12], another possible mechanism for these ferromagnetic La$_{1-x}$R$_x$MnO$_3$ and Nd$_{1-x}$R$_x$MnO$_3$ thin films is proposed to explain the colossal MR. It is suggested that the abnormal large MR in these compounds is induced by the spin-spin correlation fluctuation scattering, the magnetic property and the diagonal resistivity in different magnetic fields agree with the experimental results very well. The Hall effect is one of the important properties and may distinguish the present mechanism from the metal-insulator transition mechanism [11], so it is useful to predict the Hall resistivity behavior. In this letter, the Hall resistivity and the magnetic property for temperature T and magnetic field B are obtained. The rest is arranged as following, in Sec.II, the formalism is described; the results and discussions are given in Sec.III, and the conclusion is drawn in Sec.IV.

II. FORMALISM

In La$_{1-x}$R$_x$MnO$_3$ and Nd$_{1-x}$R$_x$MnO$_3$ compounds, because of the crystalline field effect, the 3d energy level of the Mn ion is split into the low-energy triplet, t$_{2g}$, and the high-energy doublet, e$_g$, therefore the three d-electrons of Mn$^{+3}$ and Mn$^{+4}$ ions first fill the low t$_{2g}$ band, and the extra d-electrons in Mn$^{+3}$ will have to fill the high e$_g$ band, these two bands are separated about 1.5 eV [17]. Thus the three d-electrons in filled t$_{2g}$ band forms a localized core spin through the strong Hund’s coupling [13-16], the core spins tend to align parallelly through the double exchange interaction through Mn$^{+3}$-O$^{-2}$-Mn$^{+4}$ and form ferromagnetic background. The electrons in e$_g$ band are mobile and responsible for electric conduction in these systems. In this framework, the model Hamiltonian for the mobile electrons moving in the ferromagnetic background is described:

$$H = H_0 + V$$  \hspace{1cm} (1)
\[ H_0 = \sum_{k\sigma}(\epsilon_k - \sigma\mu_B B)c_{k\sigma}^\dagger c_{k\sigma} - \sum_{<ij>} AS_i \cdot S_j - \sum_i g\mu_B B S_i^z \]  

\[ V = -\frac{J}{N} \sum_{i,k,q} \sum_{\mu\nu} e^{iR_i} S_i \cdot c_{k+q\mu}^\dagger \sigma_{\mu\nu} c_{k\nu} \]  

Where \( H_0 \) describes the bare energies of the mobile d-electrons and the ferromagnetic background, \( V \) is the coupling between the mobile electrons and the core spins. In Eq.(2), \( \epsilon_k \) represents the energy spectrum of mobile (or conduction) electrons with respect to the Fermi energy \( E_F \); \( A \) denotes the effective ferromagnetic exchange constant between manganese ions, and only the nearest-neighbor interaction is considered; \(-g\mu_B B\) is Zeemann energy in the magnetic field \( B \). In Eq.(3), the conduction electron is scattered from state \( k\nu \) to state \( k+q\mu \) by the localized spin \( S_i \); \( J \) denotes the coupling between the conduction electrons and the core spins. One notes that in the external magnetic field and the internal molecular field of ferromagnetically ordered state, the conduction band of the system will be split, this splitting is to move the position of the conduction band with respect to the Fermi surface, thus the mean-field spectrum of the conduction electron with state \( k\sigma \) is

\[ \epsilon_{k\sigma} = \epsilon_k - \sigma(\mu_B B + J < S^z>). \]

By the scattering theory [12], the lifetime of the conduction electrons between two scatterings, \( \tau \), is:

\[ \tau^{-1} = \frac{\pi}{\hbar} \frac{J^2 D(0)}{4} \sum_{k\sigma\bar{\sigma}} f_{k\sigma}(1 - f_{k\sigma})f_{k+q\bar{\sigma}}(1 - f_{k+q\bar{\sigma}})[< S_q^- S_{-q}^+ > + < S_q^- S_{-q}^+ > + 8 < S_q^z S_{-q}^z > ] \]

Where \( D(0) \) is the density of states of the conduction electrons near the Fermi surface, Dirac-Fermi distribution function \( f_k = 1/[e^{\beta(\epsilon_k - \epsilon_F)} + 1] \). Then one can obtain the diagonal conductivity through the Drude formula, \( \rho_{xx} = \frac{m}{ne^2\tau} \), here \( n \) is the density of carrier
concentration, and \( m \) the effective mass. With the diagonal resistivity, one can easily derive the Hall conductivity: in steady-state,

\[
\sigma_H = \frac{\sigma_{xx}^2}{ne} B_{eff}
\]  

(5)

or the Hall resistivity:

\[
\rho_H = \frac{ne \rho_{xx}^2}{B_{eff}}
\]

(5')

where \( B_{eff} \) is effective field, \( B_{eff} = |B + zA < S > / \mu_B| \).

From Eqs. (4) and (5), one could qualitatively understand the temperature-dependence of the Hall resistivity. At zero-temperature limit \( (T \to 0 \text{ K}) \), \( \rho_{xx} \) approaches zero because of the Pauli exclusion principle, so \( \rho_H (T \to 0) \approx 0 \); however at high temperature limit \( (T \gg T_c, E_F) \), \( \rho_{xx} \) in different magnetic field approaches the same value, the Hall resistivity mainly depends on the effective magnetic field. In this situation, the diagonal and the Hall resistivities may exhibit some different behaviors. In the mediated temperature range \( (0 < k_B T << E_F) \), especially at the temperature near the Curie point, the diagonal resistivity exhibits a maximum, therefore the Hall resistivity is also to exhibit a maximum, however, because of the effect of magnetic field, the position of the maximum of the Hall resistivity is smaller than that of the diagonal ones.

III. RESULTS AND DISCUSSIONS

In quasi-2-dimensional systems, the lattice constant is \( a = 3.89 \text{ Å} \), and the coordinate number is \( z = 4 \). The theoretical parameters is from La-Ca-Mn-O system, while the results can be applied for other similar systems. In the calculation, several parameters need to be determined by the experiments and the electronic structure calculation, for simplicity, the
reduced resistivity is adopted here.

The dependence of the spontaneous magnetization and the Hall resistivity on temperature is shown in Fig.1, for comparison, the diagonal resistivity is also shown in Fig.1. The ferromagnetic-paramagnetic transition occurs within a wide temperature range, because of the critical fluctuation and the low-dimensional character, the temperature relation of the spontaneous magnetization has a long tail, the transition temperature is broaded significantly. The electrons moving in the transverse direction is also scattered by the spin-spin correlation fluctuation near the critical point, therefore the Hall resistivity also exhibits a maximum. In the meantime, the magnetic field $B$ affects the cyclotron movement of the conduction electrons, the Hall resistivity decreases with $B$, so the maximum of the Hall resistivity will not appear at the same position as that of the diagonal resistivity, the position of the maximum moves to low temperature. It can be seen clearly in Fig.1.

The field-dependence of the Hall resistivity at different temperature is shown in Fig.2. One notes that the Hall resistivity decreases monotonously when the external magnetic field is increased. The descent resistivity with the increase of magnetic field is due to the suppress of the spin-spin correlation fluctuation scattering. Below $T_c$, the spin-spin correlation is long range, the applied magnetic field has strong effect on the scattering, so the change of the Hall resistivity is large (See the Curves (1) and (2)); while above $T_c$, the short-range spin-spin correlation fluctuation dominates the scattering of conduction electrons, the external magnetic field has weak effect, so the Hall resistivity exhibits weak dependence on the magnetic field.

Since the transverse movement of the conduction electrons are affected both by the mag-
netic field and by the spin-correlation scattering, the change of the Hall resistivity may be larger than the diagonal resistivity with the variation of the magnetic field. In the present mechanism, from the curve (1) in Fig.2, the Hall resistivity may decrease two to three orders in magnitude, for comparison, the diagonal resistivity only changes one to two orders in magnitude.

IV. CONCLUSION

In conclusion, we have studied the Hall resistivity and the magnetic property of the ferromagnetic manganese-oxide compounds. The temperature-dependence of the Hall resistivity is to exhibit a maximum below the peak position of the diagonal resistivity, and the change of Hall resistivity in magnetic field will be larger than that of diagonal resistivity. The spin-spin correlation scattering between the conduction electrons and the localized spins is the intrinsic mechanism of the abnormal Hall resistivity in La-R-Mn-O and Nd-R-Mn-O compounds near the transition point. Further experiments is desired to verify our predictions.

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REFERENCES

* mailing address

1. R. M. Kusters, J. Singleton, D. A. Keen, R. McGreevy and W. Hayes, Physica B155 362 (1989).

2. R. Von Helmolt, J. Wecker, B. Holzapfeil, L. Schultz and K. Samwer Phys. Rev. Lett. 71 2331 (1993). R. Von Helmolt, J. Wecker, and K. Samwer J. Appl. Phys. 76, 6925 (1994).

3. S. Jin, T. H. Tiefel, M. McCormack, R. A. Fastnacht, R. Ramesh, and L, H, Chen Science. 264 413 (1994). J. Appl. Phys. 76, 6929 (1994).

4. S. Jin, H. M. O’Bryan, T. H. Tiefel, M. McCormack, and W. W. Rhodos Appl. Phys. Lett 66, 382 (1995).

5. G. C. Xiong, Q. Li, H. L. Ju, S. N. Mao, L. Senpati, X. X. Xi, R. L. Greene, and T. Venkatesan, Appl. Phys. Lett 66, 1427 (1995).

6. H. L. Ju, C. Kwon, Qi Li, L. Greene and T. Vankateson, Appl. Phys. lett. 65, 2106 (1994).

7. P. Schiffer, A. P. Ramirez, W. Bao and S-W. Cheong, Phys. Rev.Lett. 75, 3336 (1995).

8. N. Furukawa, J. Phys. Soc Jpn, 63, 3214 (1994).

9. J. Inoue and S. Maekawa, Phys. Rev. Lett 74, 3407 (1995).

10. A. J. Millis , P. B. Littlewood, and B. I. Shraiman, Phys. Rev. Lett 74, 3407 (1995).
11. A. Urushibara, Y. Moritomo, T. Arima, A. Asamitsu, G. Kido and Y. Tokuya, \textit{Phys. Rev. B} \textbf{51}, 14103 (1995). Y. Moritomo, A. Asamitsu, and Y. Tokuya, \textit{Phys. Rev. B} \textbf{51}, 16491 (1995).

12. Liang-Jian Zou, X. G. Gong, Q. Q. Zheng and C Y. Pan, \textit{J. Appl. Phys.}, \textbf{78}, No.4 (1996); \textit{Phys. Rev. B}, submitted.

13. C. Zener, \textit{Phys. Rev.}, \textbf{81}, 440 (1951); \textbf{82}, 403 (1951).

14. E. O. Wollen and W. C. Koehler, \textit{Phys. Rev.}, \textbf{100}, 545 (1955)

15. J. B. Goodenough, \textit{Phys. Rev.}, \textbf{100}, 564 (1955)

16. P. G. De Gennes, \textit{Phys. Rev.}, \textbf{118}, 141 (1960)

17. J. M. D. Coey, M. Viret and L. Ranno, \textit{Phys. Rev. Lett.}, \textbf{75}, 3910 (1995).
Figures Captions

Fig. 1. Temperature-dependence of the spontaneous magnetization, the Hall resistivity and the diagonal resistivity in magnetic field. Theoretical parameters for calculation: $A=145.5$ K, $J=350$ K, $B=15$ T (1) spontaneous magnetization, (2) Hall resistivity, and (3) diagonal resistivity.

Fig. 2. Dependence of the Hall resistivity on the magnetic field at different temperature. Theoretical parameters: $A=145.5$ K, $J=350$ K, (1) $T=50$ K, (2) $T=100$ K, (3) $T=80$ K.