The Temperature Dependent Anomalous Hall Effect in La-Ca-Mn-O Films

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(Abstract)

The colossal magnetoresistance of $\text{La}_{1-x}\text{Ca}_x\text{MnO}_3$ has been reported in many experiments. We present our study of the anomalous Hall effect in epitaxial $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ thin films. We have measured the temperature dependence of resistivity, magnetization and AHE coefficients between 300K and 5K for our samples grow on different substrates. From these studies, the relation between the resistivity and AHE coefficient as well as the temperature dependence of AHE coefficient are explored. Our results show that the direction of AHE is reversed below approximately 100K. This sign reversal is discussed in term of the change of band structure and the co-existence of hole-like and electron-like conduction.

Keywords: colossal magnetoresistance, thin film, Hall effects

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The colossal magnetoresistance (CMR) caused by double exchange interactions and Jahn-Teller effects [1,3] in $\text{La}_{1-x}\text{X}_x\text{MnO}_3$ (X:Ca, Sr) compounds has attracted considerable interest for both scientific studies and potential commercial applications. Transport and magnetotransport experiments show that the temperature dependent resistivity is insulating-like above T_c and metallic-like below the T_c [2]. Measurements of the Hall effect reveal that the behavior of the Hall coefficient is similar to that of the resistivity which decreases with temperature below the T_c . However, the Hall effect switches from electron-like to hole-like behavior at temperature above to T_c [7]. Due to their ferromagnetic characteristics, there is also anomalous Hall effect (AHE) in CMR materials. The behavior of the AHE coefficient is roughly proportional to either ρ or ρ^2 for different compounds [10,11], in general agreement with theoretical predictions of side-jump or skew scattering [4-6].

Although Hall measurements on CMR materials have been reported [7-11], fewer studies have been carried out in the low temperature regime. We report a detailed Hall investigation, especially on the behavior of the AHE, in the low temperature regime much below T_c in $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ epitaxial films. The samples are prepared by pulsed laser deposition on LaAlO_3 , MgO , NdGaO_3 , SrTiO_3 substrates. In this work we present data from films on MgO . Results from films on the other substrates are similar. The samples are characterized by x-ray, SEM and TEM techniques. The magnetization and

Hall measurements are conducted on Quantum design MPMS and PPMS systems from 300K to 5K.

The T_c for each of the films measured is around 260K. Figures 1a and 1b show the field dependent Hall resistance measured at different temperatures for a sample deposited on MgO. The Hall resistance is taken as the average for both field directions to remove any effect due to misalignment. At low fields there is some anomaly of Hall resistance due to magnetic hysteresis. Figure 1b shows a portion of the same data re-plotted to show the detail of field dependent AHE below the 100K.

The Hall resistance of ferromagnetic materials includes a contribution from both the NHE (due to Lorentz force) and AHE (due to side-jump or skew scattering) [4-6]. The NHE scales linearly with applied field B . The NHE coefficient, R_H , is the constant of proportionality. The AHE resistance is equal to MR_A , where M is magnetization, and R_A is the AHE coefficient. Thus, the total Hall resistivity can be expressed as[4]

$$R_H = R_H B + R_A M \quad (1)$$

When magnetic moments are totally aligned by an external field, the contribution of AHE will be constant. In this regime, only the NHE has an increasing contribution to the Hall resistance. Thus, the AHE can be determined through a linear extrapolation of the Hall resistance at high field to determine the value at zero field. The behavior of the high field Hall resistance influences how well the AHE coefficient can be determined. The temperature dependent $R_A(T)$ is shown in Fig. 2. The trend of $R_A(T)$ is similar to $\rho(T)$

which decreases with temperature. But, it decreases much faster than $R(T)$ which predicts $R_A(T) \propto \rho(T)^n$, ($n > 1$). In addition, below 100K, the sign of AHE coefficient, R_A changes. This effect is difficult to observe in field dependent Hall measurements because the signal is small. It is further obscured due to the hysteresis effects. However, the excellent linear behavior (Fig. 1b) of the NHE in the high field regime allows an accurate value of AHE to be determined with an extremely small error.

Although the mechanism that leads to the change of the direction of AHE is not clear, we can suggest two possible explanations. One possibility is a change of band structure with decreasing temperature, leading to a change in AHE. In the transition metal ferromagnet NiFeAu, the AHE changes sign with composition. This effect has been attributed to a change in the band structure as the composition varies [5]. However, in the situation presented here, such a change in band structure without a corresponding phase change would be highly unusual. In the measurement of the NHE, only a smooth change in R_H is observed, suggested there are no abrupt phase changes. Furthermore, no such changes in band structure have been reported for this system in this temperature regime. Nevertheless, in an unconventional magnetic system like these perovskites in which the electronic and magnetic properties are so closely linked, such a possibility cannot be excluded.

A second possibility is that both hole-like and electron-like carriers co-exist in this material and the relative contribution of these two different carriers changes as a function

of temperature. The contribution to the AHE would be in opposite direction for these two different carriers. Therefore, if the contribution of one changed more as a function of temperature a change in sign could result. Although this is also a rather unusual proposition in conventional ferromagnets, the possibility that these two types of carriers co-exist in the material does have some experimental support. Based on the NHE measurements, the carrier density at $T=5\text{K}$ is calculated to be $3.12 \times 10^{22} \text{ cm}^{-3}$. This yields 1.8 carriers per Mn site, which is higher than predicted for this composition assuming a single type of carrier. This discrepancy can be accounted by the co-existence of both electron-like and hole-like carriers. However, the temperature dependence of the contribution of these carriers to the AHE remains to be established in order to confirm or exclude this possible explanation. Clearly, further experimental and theoretical work will be required to fully explanation this unusual behavior in the AHE.

We have observed a reversal in the sign of the anomalous Hall effect in La-Ca- Mn-O thin films. The change in sign occurs at a temperature around 100K. From the normal Hall effect measurements, we have found that the carrier density in the low temperature regime studied exceeds predicted values, and conclude that both hole-like and electron-like carrier co-exist in this system. Base on these results, we speculate that the change in sign of the AHE may be due to differences in the temperature dependence of these two types carriers. An alternative possibility is a change in band structure as function of

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Caption:

1. Field dependent Hall resistance on different temperature for epitaxial films deposited on MgO substrate. (a) 5K(O), 25K($\square$), 50K($\diamond$), 65K(x), 100K(+), 150K(Δ), 175K($\bullet$), 220K($\blacklozenge$), and 240K($\blacktriangle$). (b) 5K($\bullet$), 25K($\blacksquare$), 65K($\blacklozenge$), 100K($\blacktriangle$), and 150K($\blacktriangledown$).
2. The temperature dependent AHE resistance for epitaxial films deposited on MgO substrate. The inset is the same data plotted up to 250K.

Fig. 1a

Fig. 1b

Fig 2