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Effect of Magnetic Field and Temperature on the Exchange Bias in Phase-Separated $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15)

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Abstract: The exchange bias phenomena of phase-separated $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15) samples were systematically investigated in this paper. The samples were prepared using conventional solid state reaction method. When the $Nd_{1-x}Sr_xCoO_3$ samples cooled down in magnetic field below freezing temperature, the hysteresis loops shifted along the magnetic field axis. Moreover, exchange bias of $Nd_{1-x}Sr_xCoO_3$ is strongly dependent on the field and the temperature. The influence of magnetic field on the relative ratio of the coexisting phases may be responsible for these behaviors. Therefore, our study confirmed that in phase-separated system, the exchange coupling at the interface between the ferromagnetism clusters and the spin glass regions may induce interfacial exchange anisotropy.

Keywords: Phase separation, exchange bias, exchange coupling.

1. INTRODUCTION

When samples with a ferromagnetic-antiferromagnetic (FM-AFM) interface cool down in the magnetic field from above Neel temperature, hysteresis loops shift towards the magnetic field axis when the hysteresis loops are measured under the Neel temperature, namely the exchange bias. Exchange bias is induced by unidirectional anisotropy caused by exchange-coupling at the FM-AFM interface. In 1956, Meiklejion *et al.* found exchange bias by studying Co particle shrouded by CoO. Ever since, people have found exchange bias at FM-AFM /Ferri-FM/Ferri-AFM interfaces [1-6]. Exchange bias exists in mono-crystal and poly-crystal samples and thin film samples [7-15], suggesting that exchange bias is an internal trait of these systems, but not related to synthesis methods. In the recent years, exchange bias has also been found in the spin glass. Exchange-coupling at ferromagnetic and spin glass interface induces exchange bias [16-18].

This thesis studied the exchange bias of cobalt oxide $Nd_{1-x}Sr_xCoO_3$ (x=0.10, 0.15). In research, it is considered that cobalt oxides are composed of ferromagnetic cluster, non-ferromagnetic matrix and spin glass, and that spin glass exists between ferromagnetic cluster and non-ferromagnetic matrix, forming an interface around ferromagnetic cluster [19-21]. Under such circumstance, phase separation of $Nd_{1-x}Sr_xCoO_3$ causes the formation of a ferromagnetic /spin glass interface. Hence, we studied the hysteresis loops of $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15) when the field cooled down.

Results show that exchange bias is strongly dependent on the temperature and the magnetic field.

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2. EXPERIMENT

Poly-crystal samples $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15) were synthesized with standard solid-state reaction method. Firstly, highly purified Nd_2O_3 was pre-sintered for four hours at 800 ℃. Subsequently, a stoichiometric mixture of Nd_2O_3, $SrCO_3$ and Co_2O_3 powder was acquired; it was then pre-sintered for 48 hours at 1 000 °C after grinding and tablet compressing. Next, regrinding and re-tablet compressing occurred, and the sintering temperatures were set as 1 100 °C and 1 200 °C respectively, while the sintering time was set at 48 hours; the sample synthesis was completed until the temperature dropped down gradually to room temperature for 12 hours.

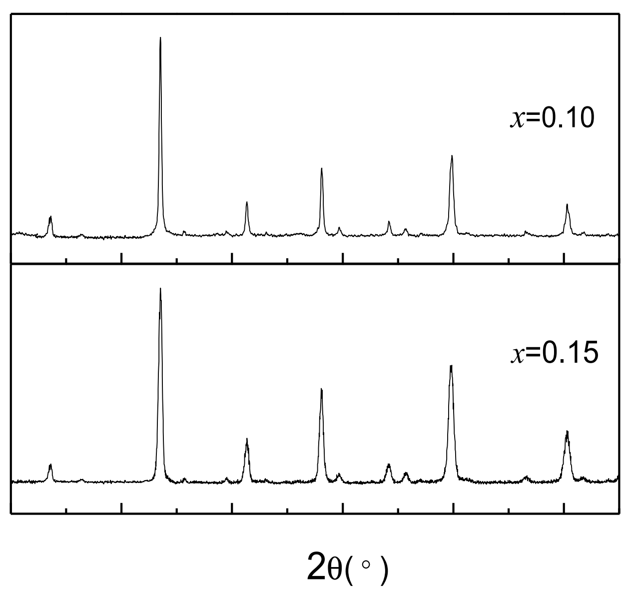

Fig. (1). XRD spectrogram of poly-crystal sample $Nd_{1-x}Sr_xCoO_3$ (x=0.10, 0.15) at room temperature.

X-ray diffraction (XRD) (Fig. **1**) power pattern was collected using the Bede D[1] XRD spectrometer with Ni-filtered Cu *K*α radiation. The room temperature XRD pattern showed that the sample is single phase with orthorhombic structure. Magnetic testing adopts the physical properties measurement system (PPMS) of the Quantum Design.

3. RESULTS AND DISCUSSION

For the condition of field-cooled (FC), hysteresis tests were conducted on samples (x=0.10) at 10 K and 25 K to analyze the causes of exchange bias. For each measurement, the field is always 5 KOe when the temperature drops from 300 K to the testing temperature.

Fig. (**2**) shows the *M-H* curve (x=0.10) at 10 K. The illustration is an enlarged view of the center of *M-H* curve. It can be observed from the figure that samples are characterized by obvious exchange bias at 10 K: H_E=50 Oe, M_E=0.037 emu/g. The vertical movement in the center of the hysteresis loops is defined as M_E, and horizontal movement *as* H_E. $M_E=(M_{up}+M_{down})/2$. M_{up} and M_{down} are the intersections of hysteresis loops with M; $H_E=-(H_{right}+H_{left})/2$. H_{right} and H_{left} are the intersections of hysteresis loops with H. Fig. (**3**) shows the *M-H* curve (x=0.10) at 25 K. The illustration at the bottom right is an enlarged view of the center of *M-H*. It can be observed from the figure that when the temperature reaches 25 K (above the freezing temperature), H_E and M_E of the samples are both zero, and exchange bias disappears. But in the upper left illustration of Fig. (**3**), samples (x=0.15) still display exchange bias when the temperature reaches 25 K (below the freezing temperature): H_E=283Oe, M_E=0.52emu/g.

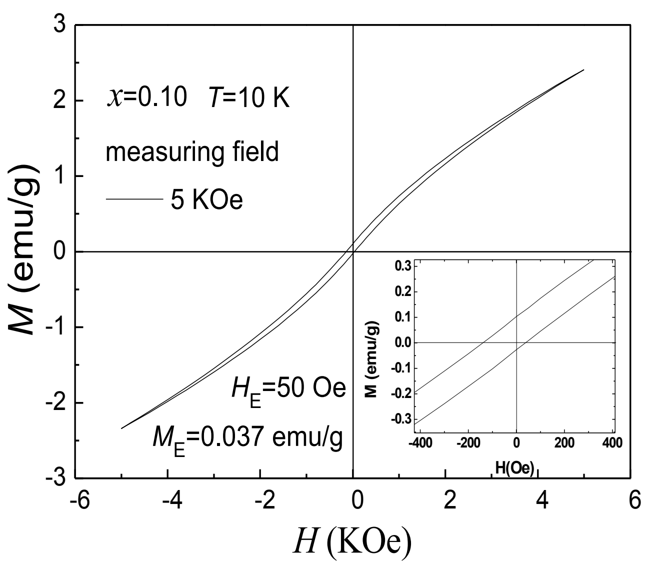

Fig. (2). The *M-H* curve (x=0.10) at 10 K on condition of H_{cool}=100 Oe. The illustration is an enlarged view of the center of *M-H* curve.

Around freezing temperature, exchange bias disappears, which is very typical at FM/SG interfaces [12, 16-17]. When samples cool down on the condition of FC past T_C, the magnetic moment of the ferromagnetic layer turns to the external magnetic field, while that of spin glass is still characterized by the disorder. When the temperature drops below the freezing temperature, due to exchange-coupling at the ferromagnetic cluster and spin glass interface, the magnetic moment at the spin glass interface may not randomly freeze. Due to exchange-coupling, the magnetic moment of the spin glass layer is arranged in a certain direction close to the ferromagnetic cluster. When the direction of the external field is reversed, the magnetic moment in the ferromagnetic region starts to spin, while that in the SG region stays unchanged. Besides, due to exchange-coupling, the magnetic moment in the spin glass interface exerts the influence of torque on the magnetic moment of the ferromagnet, keeping the original spin direction of the ferromagnetic cluster. Since the effect of magnetic moment needs to be overcome, the magnetic field that changes the ferromagnetic is high. When the direction of the external field is changed again, due to the effect of micro-torque, the magnetic moment at a small magnetic field spins. Thus, H_E appears referred to as the exchange bias.

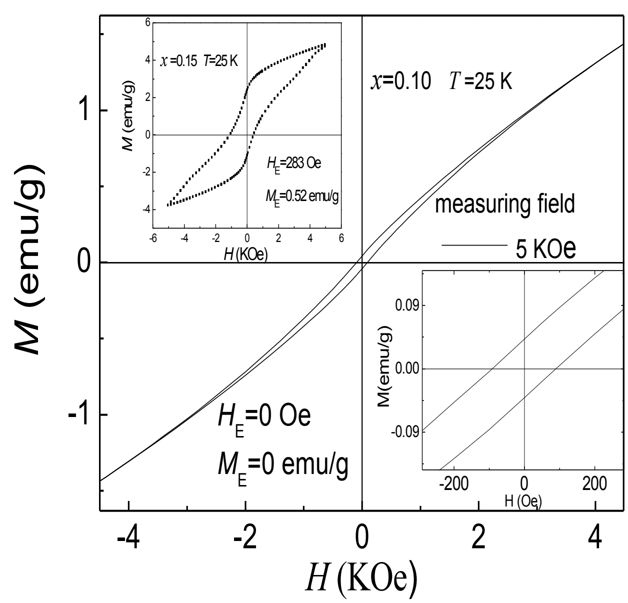

Fig. (3). The *M-H* curve (x=0.10) at 25 K on condition of H_{cool}=100 Oe. The illustration at bottom right is the enlarged view of the center of *M-H*; the upper left illustration is the curve (x=0.15) at 25 K.

The hysteresis loops display vertical movement below the freezing temperature, indicated by M_E. This is because there is a competition of energies at FM/SG interface. In the external magnetic field, magnetic behavior is mainly influenced by four energies, including anisotropy energy of FM cluster E_F and Zeeman energy E_Z, exchange energy at FM/SG interface E_{int} and anisotropy energy of SG E_S [3-4,16]. Effective Zeeman energy $E_{Zeff}=|E_Z|-|E_F|$ is introduced. When $E_{Zeff}<E_S$ and $E_{Zeff}<E_{int}$, Zeeman energy is feeble and it is not able to overcome the barrier at the interface or to reverse the magnetic moment of the spin glass. After field cooling, the magnetic moment of ferromagnetic cluster gets frozen in the direction of the external field. Thus, the hysteresis loops display biased magnetic moment in the vertical direction. For samples (x=0.1, 0.15), the fields are both 5 KOe. Zeeman energy E_Z is feeble. Thus, the bias M_E appears in the direction of the magnetic moment of hysteresis loops.

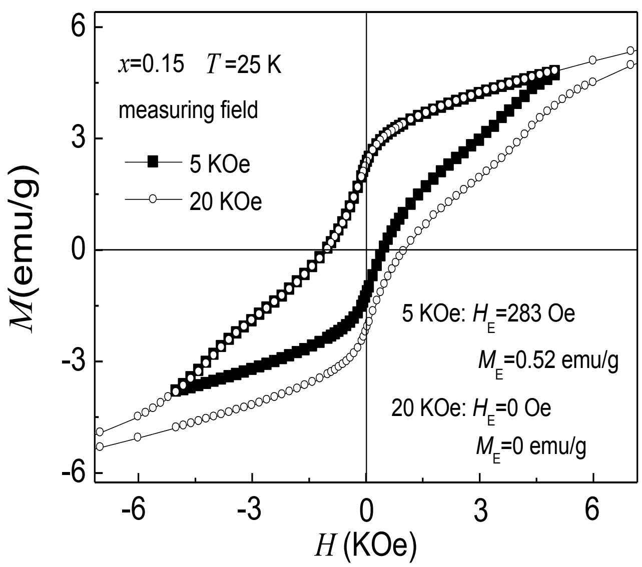

Fig. (4). the *M-H* curve of $Nd_{0.85}Sr_{0.15}CoO_3$ samples at 25 K on condition of FC.

The research reveals the relevance between exchange bias and the external field [7, 12, 16, 18]. Fig. (**4**) includes hysteresis loops at different fields on condition of FC (x=0.15). When the field is 5 KOe, exchange bias is apparent. H_E=283 Oe, M_E=0.52emu/g. When the field is 50 KOe, exchange bias disappears.

While the field increases, exchange bias is apparently lessened and disappears in high magnetic field. This is because the relative ratio of coexisting phases in the system is affected by the external field. The same can be found in the research conducted by Tang, *et al.* on $La_{1-x}Sr_xCoO_3$ [16], and Mao, *et al*. on $La_{0.8}Sr_{1.2}CoO_4$[18]. On one hand, in $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15), ferromagnetic cluster increases in external field while the spin glass decreases in the external field. The proportion of spin glass decreases with the increase in ferromagnetic cluster and the damage of spin glass. When the external field is high enough, relatively speaking, the effect of the magnetic moment of spin glass on that of ferromagnetic is feeble, and the ferromagnetic cluster is completely reversed in high magnetic field. Thus, the exchange anisotropy at the interface disappears and the horizontal movement H_E of hysteresis loops disappears. This is different from the traditional exchange bias. The exchange bias is strongly dependent on the external field. This dependence suggests that when phase-separated cobalt oxide cools down in static magnetic field, the exchange effect at ferromagnetic cluster and spin glass interface induces unidirectional anisotropy. On the other hand, since Zeeman energy increases with the increase in field, under the influence of external field, frozen ferromagnetic cluster starts to spin and vertical movement M_E of hysteresis loops decreases. When Zeeman energy increases to the extent where it can overcome the coupling of the interface, the magnetic moment of ferromagnetic is completely reversed. In the high magnetic field, M_E disappears [19-21].

CONCLUSION

To conclude, this thesis observed exchange bias in phase-separated cobalt oxide $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15). Through studying the effect of exchange bias of $Nd_{1-x}Sr_xCoO_3$, it can be observed that exchange bias in the system is strongly dependent on the magnetic field and temperature. Since different phases in $Nd_{1-x}Sr_xCoO_3$ change in different fields, when the external field is high enough, the spin glass is damaged, the ferromagnetic cluster is reversed and the exchange bias disappears. Thus, the research on the exchange bias suggests that in $Nd_{1-x}Sr_xCoO_3$(x=0.10, 0.15), located between the ferromagnetic and non-ferromagnetic field, the spin glass forms an interface. Since there is exchange between the ferromagnetic cluster and the spin glass, unidirectional anisotropy is induced at the interface, and thus the appearance of exchange bias occurs.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Dobrynin AN, Levev DN, Temst K, *et al*. Critical size for exchange bias in ferromagnetic-antiferromagnetic particles. Appl Phys Lett 2005; 87: 0125011-2.
[2] Bianco LD, Fiorani D, Testa AM, *et al*. Field-cooling dependence of exchange bias in a granular system of fe nanoparticles embedded in a Fe oxide matrix. Phys Rev B 2004; 70: 052401-4.
[3] Nogues J, Ivan K. Exchange bias. J Magn Magn Mater 1999; 192: 203-11.
[4] Gruyters M. Spin-glass-like behavior in CoO nanoparticles and the origin of exchange bias in layered CoO/Ferromagnet structures. Phys Rev Lett 2005 ; 95: 0772041-3.
[5] Passamani EC, Larica C, Marques C, *et al*. Exchange bias and anomalous vertical shift of the hysteresis loops in milled Fe/MnO_2 material. J Magn Magn Mater 2006; 299: 15-8.
[6] Kirby HF, Eggers TM, Jayathilaka PB, *et al*. Exchange bias of Mu-metal thin films. J Magn Magn Mater 2012; 324: 4151-4.
[7] Guo HW, Qun ZX, Hai-Feng D, *et al*. Intrinsic exchange bias effect in phase-separated $La_{0.82}Sr_{0.18}CoO_3$ single crystal. J Phys Condense Matter 2008; 20: 445209.
[8] Yang DZ, Kapelrud A, Saxegaard ME, *et al*. Training and recovery behaviors of exchange bias in FeNi/Cu/Co/FeMn spin valves at high field sweep rates. J Magn Magn Mater 2012; 324: 3223-6.
[9] Öztürk M, Demirci E, Topkaya R, *et al*. Effect of exchange bias on magnetic anisotropies in Fe/CoO bilayers. J Supercond Nov Magn 2012; 25: 2597-603.
[10] Guo S, Liu W, Liu X.H, *et al*. Influence of ferromagnetic layer on the exchange coupling of antiferromagnetic NiO-based films. J Magn Magn Mater 2012; 324: 3933-6.
[11] Tribedi B, Saravanan P, Ravi S. Antiferromagnetism and the effect of exchange bias in $LaCr_{1-x}Fe_xO_3$ (x=0.40 to 0.60). J Supercond Nov Magn 2013; 26:1645-8.
[12] Kun TY, Sun Y, Zhao-hua C. Cooling field dependence of exchange bias in phase-separated $La_{0.88}Sr_{0.12}CoO_3$. J Appl Phys 2006 ; 100: 023914.
[13] Rocha JC, Costa BV, Coura PZ, *et al*. Magnetic behavior of a nano-disk constrained in an antiferromagnetic substrate. J Magn Magn Mater 2012; 324: 2342-8.
[14] Sánchez T, Sato TR, Grssinger R, *et al*. Exchange bias behavior in $Ni_{50.0}Mn_{35.5}In_{14.5}$ ribbons annealed at different temperatures. J Magn Magn Mater 2012; 324: 3535-7.

[15] Del BL, Spizzo F, Tamisari M, *et al*. Dependence of exchange bias on the field-cooled remanent magnetic state in Ni/NiO nanogranular samples. Solid State Commun 2011; 151: 351-3.

[16] Kun TY, Yong S, Zhao-hua C. Exchange bias associated with phase in the perovskite cobaltite $La_{1-x}Sr_xCoO_3$. Phys RevB 2006; 73: 1744191-2.

[17] Mingtao L, Zhenjie F, Huiling Y, *et al*. Exchange bias in structure-phase separated $K_{0.8}Fe_{2-x}Ni_xSe_2$ (x=0.015) single crystal: interface evidence. J Magn Magn Mater 2012; 324: 3058-64.

[18] Jinhua M, Yu S, Xianjie W, *et al*. Intrinsic exchange bias and its origin in spin-glass-like disordered $La_{0.8}Sr_{1.2}CoO_4$ cobaltite. Physica B 2013, 427: 37-41.

[19] kun TY, Young S, Zhao-hua C. Glassy magnetic behaviors in the phase-separated perovskite cobaltites. Phys Rev B 2006; 73: 012409.

[20] Wu J, Leighton C. Glassy ferromagnetism and magnetic phase separation in $La_{1-x}Sr_xCoO_3$. Phys Rev B 2003; 67: 1744081-10.

[21] Stauffer DD, Leighton C. Magnetic phase behavior of the ferrimagnetic doped cobaltite $Nd_{1-x}Sr_xCoO_3$. Phys Rev B 2004; 70: 2144142-6.

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