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Room temperature exchange bias in $SmFeO_3$ single crystal

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ABSTRACT

Exchange bias phenomenon is generally ascribed to the unidirectional magnetic shift along the field axes at interface of two magnetic materials. Room temperature exchange bias is found in $SmFeO_3$ single crystal. The behavior after different cooling procedure is regular, and the training behavior is attributed to the athermal training and its pinning origin is attributed to the antiferromagnetic clusters. Its being single phase and occurring at room temperature make it an appropriate candidate for application.

1. Introduction

Exchange bias (EB) was initially observed in Co particles coated with a layer of CoO by Meiklejohn and Bean [1]. It refers to the shift of magnetic hysteresis loop along the field axes after the sample is cooled in a magnetic field. It have been exploited in several technological applications such as read heads of recording devices [2] and magnetoresistive random access memories (MRRAM) [3], and have been proposed for technological applications in stabilizing magnetization of superparamagnetic nanoparticles [4,5] or to improve the coercive field and energy product of permanent magnets [6]. EB has been found in a large number of heterostructures such as core–shell nanoparticles, magnetic multilayers, thin films [7–10] and bulk compounds with intrinsic phase separation [11–13]. Recently, exchange bias has been noticed in several single phase materials [14,15]. However, EB in such systems occur well below room temperature. A single crystal with exchange bias at room temperature will be ideal for application.

$SmFeO_3$ is a distorted perovskite with rich magnetic properties. It is canted antiferromagnetic (AFM), with a high ordering temperature 680 K. The magnetization reversed spontaneously at about 5 K due to the compensation of momentum along [100] axes. Meanwhile, a temperature induced magnetization reverse is observed from compensating temperature to well above room temperature [16,17]. Herein, we are motivated in reporting the exchange bias phenomenon in $SmFeO_3$. Its occurrence in single crystal at room temperature, make it an appropriate candidate for both application and multi-approach investigation. For example, spin valve device, which has exchange biased layers containing one antiferromagnetic layer and one ferromagnetic layer, can be simplified using such materials with carrier doping. Meanwhile, both the exchange bias coexisting with negative magnetization and temperature induced magnetization reverse make it an ideal candidate for multi-parameter modulation spintronic. The spin-reorientation temperature of $SmFeO_3$, which may be in accordance with the blocking temperature, is far above room temperature [17]. This offers large possibility of modulation in a wide temperature range.

2. Experimental details

Single crystal of $SmFeO_3$ is grown in a four-mirror optical-floating-zone furnace (FZ-T-4000-H-VI-VPO-HF-PC, Crystal Systems Corp.) using four 1 kW halogen lamps as the infrared radiation source with flowing air. During the growth process, the molten zone moves upwards at a rate of 5 mm/h, with the seed rod (lower shaft) and the feed rod (upper shaft) counter rotating at 25 rpm in air flow of 50 cc/min. The compositional homogeneity and crystal structure are confirmed by X-ray diffraction (XRD) and Laue back scattering. All results confirm the good quality of the crystals [17] and are well indexed according to a Pbnm space

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group.

Measurements of magnetization as a function of temperature (M–T) and magnetic field (M–H) are performed using Quantum Design MPMS XL-7 and (SQUID) VSM. For the zero-field cooling (ZFC) measurement, the sample is simply heated to 973 K and hold for 30 min to achieve a uniform temperature of the sample. Field cooling (FC) is achieved using a high temperature oven of MPMS XL-7 with a cooling field of $\pm$1 T and temperature from 750 K to 300 K.

3. Results and discussion

We first look at the magnetic feature of single crystal $SmFeO_3$ well above room temperature. The magnetic anisotropy dependence of temperature can be obtained by applying external magnetic fields along different axes. According to earlier reports, below its Néel temperature T_N=680 K, $SmFeO_3$ becomes a canted antiferromagnet with a weak ferromagnetic vector (FM) from Fe-sublattice along [001] axes. The spin reorientation transition (SR) of the Fe-sublattice, where M_{100}–T and M_{001}–T show crossover behavior with exchanged magnetization magnitude, exists between 450 and 480 K (T_{SR}) [17]. All of our measurements were performed with the field along [100] axes. To avoid the complex magnetization jumping stated by Cao et al. [17], we have taken the following means. Firstly, a 6000 Oe field is used to make the magnetization positive, which is previously achieved using field cooling. Secondly, a small field of 100 Oe is applied to avoid temperature induced magnetization jump, during which measurement the difference between opposite magnetization is obtained. Finally, a high field as large as 1 T is used in a high temperature oven to measure the magnetization above room temperature. The temperature dependence of both high consistent magnetization behaviors under different field in Fig. 1(b) shows its saturation, which is helpful in avoiding the minor loop effect [18,19] in our later discussion. Our temperature dependence of magnetization is in highly accordance with the previous reports [16,17].

An unexpected phenomenon is noticed in our M–H measurements. As shown in Fig. 2(a), the magnetic loops shift horizontally after FC and even after a cycle of measurement after ZFC. Compared with the small coercive field, the absolute shift has a high contrast. It reverses after an opposite cooling field, as can be clearly observed in Fig. 2(a). Such behavior largely hints that it is intrinsic for the single crystal. This drives us to further investigate it according to exchange bias. The exchange bias field is defined as $H_{EB}=(H_+ + H_-)/2$, where $H_\pm$ are the positive and negative intercepts of the magnetization curve with the field axes, while the coercive field is defined as $H_C= (H_+ - H_-)/2$. The main indications due to the exchange bias effect in a system are: (i) a shift of the field-cooled (FC) hysteresis loop along the magnetic field axes (in a magnetic field dependent dc-magnetization study), (ii) an enhancement of the coercive field in a FC-hysteresis study compared to the corresponding zero field-cooled (ZFC) case, and (iii) the training effect [20]. Since we have noticed the horizontally shift, both an enhancement of coercive field and training effect are required to check. As shown in Fig. 2(a), the first loop of ZFC, whose horizontal shift $H_h=(H_+ \pm H_-)/2$ is -0.7 Oe, should be attributed to instrument error. So a contrast of coercive field is obtained between ZFC and FC measurements, as can be easily noticed in Fig. 2(a), negative and positive FC (NFC and PFC) have coercive fields of 172.4 Oe and 165.6 Oe respectively. Regarding that the coercive field of ZFC is 125.9 Oe, the coercive field is enhanced in accordance with the emergence of horizontal shift. As can be seen in Fig. 2(b)–(d), right after the first hysteresis loop, coercive field variation reach the measurement precision error and could not be clarified. Similar behavior have been noticed in polycrystalline $Eu_{0.5}Sm_{0.5}MnO_3$ [21], which is also reported to have exchange bias phenomenon. Considering the coercive field keeps constant after the second loop, the only first two horizontal shift values are shown in Fig. 2(b)–(d), labeled H_{EB} and H_h, referring to the exchange bias fields and absence of exchange bias right after ZFC. Furthermore, it is still worth noting that exchange bias reproduce after a cycle of measurement after ZFC. Exchange bias after zero field cooling is also reported in polycrystalline $SmCrO_3$ [14].

The training effects are now discussed in terms of thermal and athermal training, and both show the different behaviors. When athermal training dominants, the EB field of the first loop is significantly higher than the EB field of the subsequent loops. After the second loop the EB field remains constant. When thermal training dominants, the EB field of the first loop is still much higher but after the second loop it is contiuously decreasing [22]. According to the above cases the training in our system should be

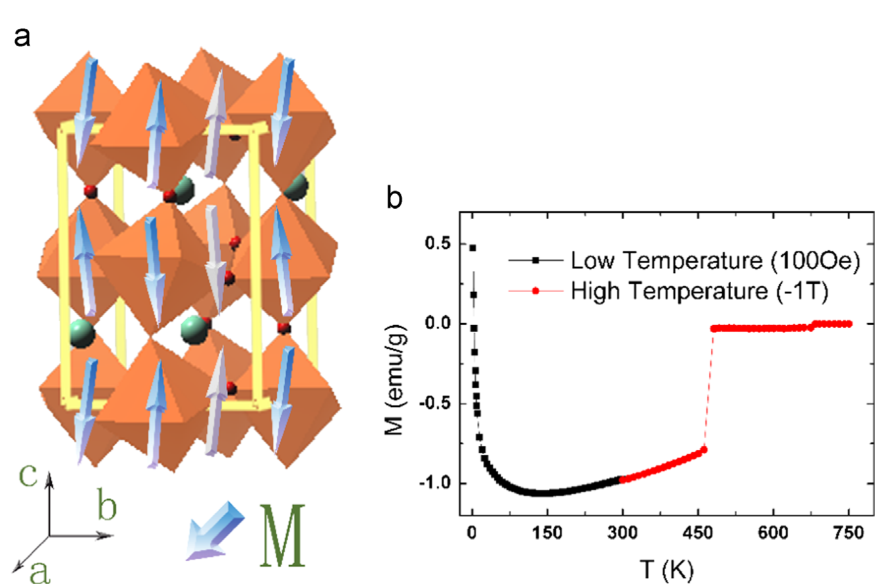

Fig. 1. (a) Magnetic structure of Fe^{3+} at room temperature, M refers to the magnetization direction. (b) Temperature dependence of magnetization. Black squares and red diamonds are low temperature and high temperature magnetization obtained in different magnetic fields. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)