Physica B 433 (2014) 12–20

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Complete and incomplete jump phenomenon in the angular dependence of the noncollinear exchange bias

HongPing Yang, YuHao Bai *

College of Physics and Electronic Information, Shanxi Normal University, Linfen 041004, China

ARTICLE INFO

Article history:
Received 12 May 2013
Received in revised form
9 October 2013
Accepted 12 October 2013
Available online 19 October 2013

Keywords:
Jump phenomenon
Angular dependence of the exchange bias
Coercivity
Critical angle

ABSTRACT

The angular dependence of the exchange bias (ADEB) has been investigated in detail for ferromagnetic/antiferromagnetic bilayers with noncollinear uniaxial and unidirectional anisotropies. Two different types of the jump phenomenon, complete and incomplete jump phenomena, have been proved to occur at the orientations of the intrinsic easy and hard axes. A special position for the intrinsic easy and hard axes, which makes an angular deviation of 58.2826° from the uniaixal anisotropy axis, has been deduced by analyzing the magnetization reversal processes based on the principle of minimal energy. When the angular deviation of the intrinsic easy or hard axis from the uniaxial anisotropy axis is above the critical value of 58.2826°, the complete jump phenomenon will be shown in the ADEB. On the contrary, once this angular deviation is not more than 58.2826°, the incomplete jump phenomenon occurs, and the critical angle will be observed in the ADEB. The determined formula of the critical angle is also obtained by analyzing the magnetization reversal processes. Additionally, the extreme value problem of the exchange bias is studied in this paper. The coercivity always reaches its maximum value when the external field points along the intrinsic easy axis. The minimal coercivity occurs at the orientation of the critical angle. However, there are two orientations of the applied field to gain the maximal exchange bias field. One is the direction of the intrinsic hard axis when the complete jump phenomenon occurs at this orientation. The other one is the orientation of the critical angle under the condition that the incomplete jump phenomenon takes place at the intrinsic hard axis. The numerical calculations are consistent with the involved experimental observations, indicating that our method is valid to study the ADEB and it is an effective method to achieve the maximal exchange bias field as well as the maximal or minimal coercivity by adjusting the orientation of the external field.

Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.

1. Introduction

Over the last 2 decades, more and more efforts have been made towards the exchange bias effect, which is usually established by cooling the ferromagnetic (FM) and antiferromagnetic (AFM) systems, e.g., FM/AFM bilayers, in the presence of a magnetic field below the antiferromagnetic ordering temperature or by preparing FM/AFM systems under a magnetic field during the deposition processes. The most striking feature of exchange bias is the shift of the FM hysteresis loop, which is induced by the unidirectional anisotropy resulting from the exchange interaction between the interfacial spins of the FM/AFM systems. This unidirectional anisotropy is widely used to pin the direction of FM magnetization in today's magnetic applications, such as magnetic recording, sensors, actuators and spintronics [1–2]. Although the exchange bias effect has been studied intensively for more than 50y years, the mechanism of its characteristic, such as coercivity enhancement, positive exchange bias, training effect and asymmetric magnetization reversal, remains a subject of discussion. Complete references concerning both theories and experiments can be found in some reviews published on this subject [3–8].

The angular dependence of exchange bias (ADEB) is an important subject in the investigation of the exchange bias effect. The exchange bias field H_{EB} and the coercivity H_C, defined respectively as the shift and half-width of the hysteresis loop, are strongly influenced by the orientations of the external field. It is well known that ADEB is very informative to test the validity of the theoretical models on the exchange bias [9]. Furthermore, the types, the magnitude together with the relative orientation of the anisotropies in exchange-coupled FM/AFM systems can be obtained by fitting the measured $H_{EB}(\theta_H)$ and $H_C(\theta_H)$ curves numerically [10].

It has been confirmed by both experiments and theoretical calculations that H_{EB} and H_C can display a jump phenomenon in the ADEB for both collinear [11–14] and noncollinear [15–18] exchange bias, which respectively means that the uniaxial

---

* Corresponding author. Tel./fax: +86 357 2051132.
E-mail addresses: baiyuhao1983@yahoo.com.cn, bhy198322@163.com (Y. Bai).

0921-4526/$ - see front matter Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physb.2013.10.016

anisotropy K_U is aligned and misaligned with the unidirectional anisotropy K_E in FM/AFM systems. The noncollinear exchange bias can be established both intrinsically by interfacial spin frustration [19–21] and extrinsically by a special field cooling procedure [17,18,22], ion irradiation [23] or preparing the FM/AFM systems by the oblique sputtering deposition [24].

As far as the ADEB in the collinear exchange bias is concerned, it is found that H_{EB} reaches its maximum value, at the same time, H_C vanishes itself suddenly at the jumping points defined as the intrinsic hard axes in Bai et al.'s work [14]. This kind of the jump phenomenon has been named as the complete jump phenomenon in their paper. In fact, the same feature has also been discovered by Liedke et al. in $H_{EB}(\theta_H)$ and $H_C(\theta_H)$ curves for the noncollinear exchange-coupled NiFe/FeMn bilayers [18]. Recently, Jiménez et al. have studied the ADEB in exchange-coupled Co/IrMn bilayers with the noncollinear uniaxial and unidirectional anisotropies [17]. Though the jump phenomenon is shown, H_{EB} does not reach the maximum; moreover, H_C does not disappear after the occurrence of the jump phenomenon. The critical angles, where H_{EB} achieves its maximum and H_C together with the asymmetric magnetization reversal start to disappear, have been observed to be located behind the position of the jumping point. This feature is similar to the incomplete jump phenomenon displayed in the ADEB for the collinear exchange bias [14].

Obviously, one conclusion can be drawn from above experiments that two different types of the jump phenomenon, complete and incomplete jump phenomena, can still exist in the ADEB for the noncollinear exchange bias, although it manifests itself very differently in various materials [17–18]. The jump phenomenon of the exchange bias is associated strongly with the maximum value of the exchange bias field, which is technologically important to the design of the involved magnetoresistance devices [14,16]. As a consequence, it is very essential to supply an explanation for the complete and incomplete jump phenomenon in the ADEB, which is also the purpose of this paper. This article is organized as follows. Based on the coherent rotation model, the analysis of the magnetization reversal process and the explanation of two types of the jump phenomenon are presented in the Section 2. Additionally, the discussions about the observation of the critical angles, the amplitude of the jump phenomenon, and the extreme value problem of the ADEB are also given in the subsections of the Section 2. Finally, a summary is given in Section 3.

2. Theoretical model and numerical calculations

2.1. The initial state and the angular regions

The FM/AFM bilayers with uncompensated interface are chosen to study the ADEB. The ferromagnetic coupling is assumed to exist between the interfacial spins of the FM/AFM bilayers. The free energy per unit volume of the systems is given by [16–18,25]

$$E = K_U \sin^2\theta_F - K_E \cos(\alpha - \theta_F) - HM_S \cos(\theta_H - \theta_F), \tag{1}$$

where H and M_S are externally applied field and the saturation magnetization of FM layer, K_E and K_U are unidirectional and uniaxial anisotropy constants, the angles θ_H, α and θ_F represent the orientations of the external field, the unidirectional anisotropy, and the FM magnetization with respect to the easy axis of the uniaxial anisotropy, which is defined as x axis for simplicity. All the angles in the calculations are counted clockwise starting from the positive x semiaxis.

As mentioned in Bai et al.'s works [14,16], the competition between unidirectional and uniaxial anisotropies divides the initial magnetization state of the systems into monostable and bistable states, which determine the ADEB directly. The critical condition used to distinguish the monostable state from the bistable state can be given by $\partial E_0/\partial\theta_F = 0$ and $\partial^2 E_0/\partial\theta_F^2 = 0$, which were written as

$$\begin{cases} \frac{1}{2}\ \sin 2\theta_F - J\ \sin(\alpha - \theta_F) = 0 \\ \cos 2\theta_F + J\ \cos(\alpha - \theta_F) = 0 \end{cases}, \tag{2}$$

where E_0 is the initial energy of the systems when the applied field is absent. $J = J_E/2K_U$ is defined as the reduced exchange-coupling constant which describes the effect of the competition between unidirectional and uniaxial anisotropies [14,16]. The solution of Eq. (2), i.e., the critical exchange-coupling constant J_C that is responsible for the transition from bistable to monostable state can be derived as

$$J_C = \left[\frac{1}{(\cos\ \alpha)^{2/3} + (\sin\ \alpha)^{2/3}}\right]^{3/2} \tag{3}$$

When J is larger than J_C, the unidirectional anisotropy is dominant in the competition, thus the bilayer is in the monostable state. Correspondingly, the bilayer will present only one intrinsic easy axis θ_{F1} together with one intrinsic hard axis θ_{F2}. On the contrary, the bilayer will be in the bistable state under the condition that J is smaller than J_C. In this case, two intrinsic easy axes θ_{F1} and θ_{F3} together with two intrinsic hard axes θ_{F2} and θ_{F4} will be observed in the energy spectrum. A detailed descriptions about the monostable and bistable states together with the intrinsic easy and hard axes have been reported elsewhere [14,16].

Selecting Jiménez et al.'s parameters [17]: $J = K_E/2K_U = 8.1/5.2 \approx 1.5577$, $\alpha = 20^\circ$ to calculate $H_{EB}(\theta_H)$ and $H_C(\theta_H)$ curves. The critical exchange-coupling constant $J_C = 0.5736$ can be derived from Eq.(3) for this noncollinear angle. Therefore, the system will be in the monostable state for the reason of $J > J_C$. The positions of the intrinsic easy and hard axes, $\theta_{F1} = 12.3133^\circ$ and $\theta_{F2} = 218.1751^\circ$, can be obtained by solving Eq. (2) with the above parameters. The positions of θ_{F1} and θ_{F2} as well as the divided angular regions are illustrated in Fig. 1(a).

As observed in the Jiménez et al.'s experiment, the critical angle θ_C appears after the occurrence of the jump phenomenon at the intrinsic hard axis [17], indicating that θ_C will be located in the angular region 3, i.e., $\theta_{F2}\text{-}180^\circ \le \theta_H < \theta_{F1} + 90^\circ$ as described in Fig. 1(a). Consequently, the magnetization reversal processes when θ_H is within the scope of the angular region 3 should be discussed in detail in order to assess the critical angle. The coherent rotation

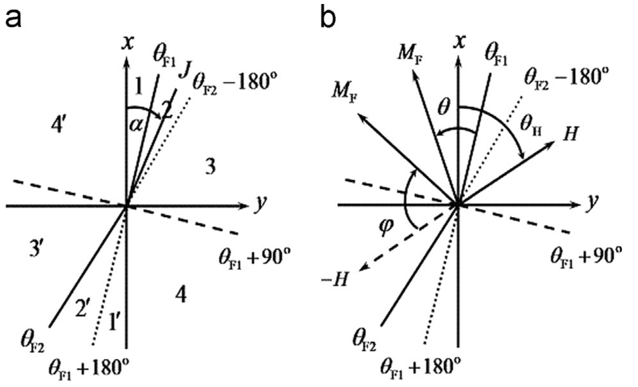

Fig. 1. (a) The schematic diagram for the positions of the intrinsic easy axis θ_{F1}, the intrinsic hard axis θ_{F2} and the corresponding angular regions. (b) The rotation of M_F in the magnetization reversal processes for the angular regions 3. The dashed line with arrow represents the opposite orientation of the applied field H. The opposite orientations of the intrinsic easy and hard axes are indicated by the dotted lines. θ and φ are the angles that M_F makes with θ_{F1} and $-H$ during its rotation in descending and ascending branches of the hysteresis loop, respectively. The parameters are taken as $J = 1.5577$, $\alpha = 20^\circ$ in the numerical calculations.

Download English Version:

https://daneshyari.com/en/article/8162844

Download Persian Version:

https://daneshyari.com/article/8162844

Daneshyari.com