Journal of Magnetism and Magnetic Materials 466 (2018) 138–142

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Research articles

Engineering of exchange bias field and magnetization relaxation with nonmagnetic dilution: The role of the misalignment between anisotropy axes

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ARTICLE INFO

Keywords:
Exchange bias
Magnetic anisotropy
Noncollinear spin structure
Magnetization relaxation

ABSTRACT

In this work, using magnetron sputtering technique we prepare and characterize a series of exchange-biased $(Fe_{70}Co_{30}/Ir_{25}Mn_{75})_3$ multilayers with antiferromagnetic layer ($Ir_{25}Mn_{75}$) doped by nonmagnetic MgO to study the misaligned effect of anisotropies on the static exchange bias field (H_{eb}) and the dynamic magnetization relaxation behavior. We demonstrate a strong correlation between the misalignment angle and H_{eb}, as well as the dynamic damping along the easy axis of the H_{eb}, and attributed this to the noncollinear spin structure in ferromagnetic layer. While a different relaxation behavior was observed for the hard axis due to the unidirectional relaxation mechanism in the exchange biased system. Our result may shed new insight in the field of exchange bias, promoting its application in low consumption spintronics devices.

1. Introduction

Exchange bias has long been the focus of scientific attention since it was discovered in 1950s [1,2], due in part to its successful and tremendous applications in various spintronic devices such as spin-orbital-torque switching of magnetization [3,4], spin transfer nano-oscillator [5] and magnetic field sensor [6]. Moreover, as an interfacial effect involving complex interaction between the antiferromagnetic (AFM) and ferromagnetic (FM) layers, the intriguing and rich physics in exchange bias also triggers extensive research interest in the past decades [7–10]. The macroscopic signature of exchange bias is a unidirectional displacement of the ferromagnetic hysteresis loop by an amount called the "exchange bias field" (H_{eb}). The origin of the unidirectional displacement or unidirectional magnetic anisotropy is associated with the pinning effect of the magnetic moment in the FM layer by the AFM layer, although underlying physics of the pinning effect is still in controversy.

Exchange bias or unidirectional magnetic anisotropy is typically established by cooling or growing an AFM/FM system in a static magnetic field, which also induces a uniaxial magnetic anisotropy in the FM layer. It had been believed that the easy direction of unidirectional anisotropy and that of uniaxial anisotropy are collinear until some recent experimental works indicate that a misalignment might exist between them in exchange-biased systems [11–13]. Although quantitative determination of the misalignment between the anisotropy axes has been achieved, the influence of this noncollinear behavior on the exchange bias system, in particular on the magnetization dynamics, is still an open question.

In this letter, we use broadband ferromagnetic resonance (FMR) technique to investigate the correlation between the misalignment of anisotropies and the exchange bias field as well as the dynamic magnetization relaxation process for the $(Fe_{70}Co_{30}/Ir_{25}Mn_{75})_3$ exchange-biased multilayers, the AFM layer ($Ir_{25}Mn_{75}$) of which is diluted by nonmagnetic MgO doping. Based on the in-plane angular dependent FMR measurements, we demonstrate that the misalignment angle β between the unidirectional and uniaxial anisotropy axes can be effectively engineered by adjusting the concentration of nonmagnetic MgO in AFM $Ir_{25}Mn_{75}$ layer. This leads to the changes in the exchange bias field. Moreover, the frequency dependent FMR measurements indicate a unidirectional magnetization relaxation behavior in the exchange-biased system, as the effective damping of the FM FeCo layer, which is a crucial parameter determining the power consumption of the relevant spintronic devices, strongly depends on the misalignment between the anisotropy axes, especially on the easy direction of exchange bias field.

2. Experiment

A series of $[Fe_{70}Co_{30}/(Ir_{25}Mn_{75})_{1-x}(MgO)_x]_3$ ($x \leq 0.09$) samples

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https://doi.org/10.1016/j.jmmm.2018.06.081
Received 13 April 2018; Received in revised form 21 June 2018; Accepted 27 June 2018

were deposited on polished SiO_2 substrates at room temperature using conventional RF magnetron sputtering. The base pressure was around 1.5×10^{-5} Pa and the sputtering pressure was kept at 0.2 Pa and 1.0 Pa for $Ir_{25}Mn_{75}$ and $Fe_{70}Co_{30}$, respectively. During the sputtering process, the gas flow rate was kept at 16 SCCM and the RF sputtering power was kept at 80 W for both $Fe_{70}Co_{30}$ and $Ir_{25}Mn_{75}$ layers. To introduce MgO into the $Ir_{25}Mn_{75}$ layer, several MgO chips were put symmetrically in a ring on the surface of the $Ir_{25}Mn_{75}$ target (co-sputtering approach) and the dilution concentration was determined by energy-dispersive spectrometer (EDS). The structural properties of the thin films were characterized by (XRD) (Brucker D8). The surface morphology was characterized by AFM (Multimode 8, Bruker Co.). As for the sputtering procedure, we first deposited $(Ir_{25}Mn_{75})_{1\text{-}x}(MgO)_x$ layer, then $Fe_{70}Co_{30}$ layer for three periods. The thicknesses of each $Fe_{70}Co_{30}$ layer and $(Ir_{25}Mn_{75})_{1\text{-}x}(MgO)_x$ layer were kept at around 5 nm and 3 nm, respectively. A static magnetic field ($\sim$ 300 Oe) was applied parallel to the substrate surface during the deposition to induce an in-plane magnetic anisotropy in the films.

3. Result and discussion

Fig. 1(a) presents X-ray diffraction patterns for the prepared $[Fe_{70}Co_{30}/(Ir_{25}Mn_{75})_{1\text{-}x}(MgO)_x]_3$ multilayers. For all samples we observe two diffraction peaks which can be corresponded to the IrMn fcc (1 1 1) and FeCo bcc (1 1 0) plane. It is interesting to note that the intensity of the diffraction peaks decreases with the increasing MgO doping concentration, it may indicate a relatively fine grains in the exchange bias multilayers with high MgO doping concentration. The surface morphology of the multilayers without doping and a doping of $x = 0.09$ are shown in Fig. 1(b) and (c), respectively. Both samples have relatively smooth surface with small root mean square roughness (Rq $\sim$ 0.99 nm and $\sim$1.02 nm for $x = 0$ and $x = 0.09$, respectively).

To investigate the misalignment between the anisotropy axes in the exchange-biased system, we performed in-plane angular dependent FMR measurements. As shown in Fig. 2(a), the samples were placed facing down on a coplanar waveguide and subjected to a microwave field h with frequencies ranging from 5 to 17 GHz. During the measurement, the samples were rotated in waveguide plane, and the direction of microwave field h was kept perpendicular to that of static field H, as shown in Fig. 2(b). For the quantitative analysis, we set the film lying in the x-y plane with its normal direction pointing to the z axis, and designate the x axis as the easy direction of exchange bias field (unidirectional anisotropy), as shown in Fig. 2(c). The parameters θ, φ are the polar and azimuthal of the magnetization (M) in the corresponding spherical coordinate system, respectively. The free energy E per unit area in the exchange-biased system can thus be given by: [14]

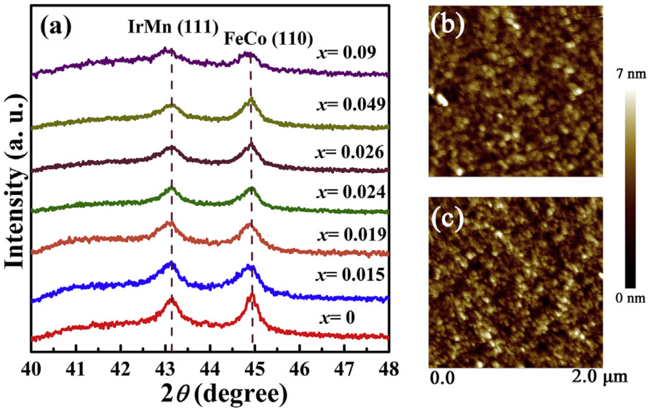

Fig. 1. (a) X-ray diffraction patterns of $[Fe_{70}Co_{30}/(Ir_{25}Mn_{75})_{1-x}(MgO)_x]_3$ multilayers with various MgO concentrations. AFM images for $[Fe_{70}Co_{30}/(Ir_{25}Mn_{75})_{1-x}(MgO)_x]_3$ multilayers at MgO concentration $x = 0$ (b) and $x = 0.09$(c).

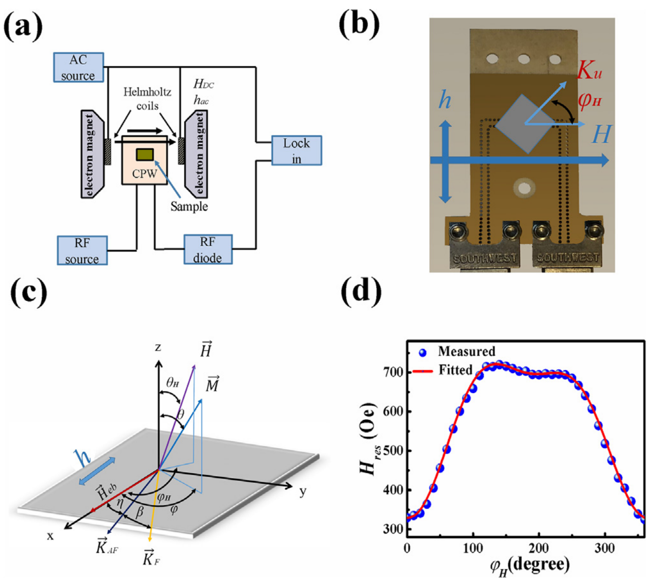

Fig. 2. (a) The FMR measurement setup consisting of the coplanar waveguide (CPW) inside the electromagnet. (b) The coplanar waveguide structure and the sample placed on top of it. The sample's unidirectional anisotropy axis (K_u) makes an angle φ_H with respect to the direction of H. (c) Spherical coordinate system used in the ferromagnetic resonance analysis. (d) Typical measured and fitted azimuthal angular-dependent curves of a resonance field H_{res} in $(Fe_{70}Co_{30}/Ir_{25}Mn_{75})_3$ multilayer.

$$E = -Mt_F H\sin\theta\cos(\varphi-\varphi_H) + (2\pi M^2 t_F - K_s)\cos^2\theta - Kt_F\sin^2\theta\cos^2(\varphi-\beta-\eta) - H_{eb}Mt_F\sin\theta\cos(\varphi-\eta) \tag{1}$$

where the first term is the Zeeman energy due to the external applied magnetic field (t_F is the thickness of the F layer), the second term is the demagnetization energy due to the perpendicular surface anisotropy (K_s denotes the surface anisotropy constant), the third term represents the in-plane uniaxial anisotropy energy (K is the uniaxial anisotropy constant), taking into account the misalignment angle β from unidirectional anisotropy, and the last term of Eq. (1) represents the surface exchange coupling energy between the AFM and FM spins. For simplicity, the angle η, which indicates the misorientation between the AFM anisotropy axis and the unidirectional anisotropy during the films deposition, is neglected [15]. The resonance condition is then derived by using Smit and Beljers relation [16],

$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{M\sin^2\theta}\left[\frac{\partial^2 E}{\partial\theta^2}\frac{\partial^2 E}{\partial\varphi^2} - \left(\frac{\partial^2 E}{\partial\theta\partial\varphi}\right)^2\right] \tag{2}$$

where $\omega = 2\pi f$ is the (angular) resonance frequency and γ is the gyromagnetic ratio. Eq. (2) can be evaluated at the equilibrium position (θ_0, φ_0) of the magnetization with equilibrium condition:

$$\left.\frac{\partial E}{\partial\theta}\right|_{\theta_0} = 0, \text{ and} \left.\frac{\partial E}{\partial\varphi}\right|_{\varphi_0} = 0 \tag{3}$$

In our case, the measurements were performed under in-plane configurations, i.e., $\theta = \theta_H = \pi/2$, $\varphi = \varphi_H$, thus the resonance field formula can be given as:

$$\left(\frac{\omega}{\gamma}\right)^2 = [4\pi M_{\text{eff}} + H_k\cos^2(\varphi_H-\beta) + H_{eb}\cos(\varphi_H) + H_{res}] \times [H_k\cos2(\varphi_H-\beta) + H_{eb}\cos(\varphi_H) + H_{res}] \tag{4}$$

where $4\pi M_{\text{eff}}$ is the effective magnetization field, H_{res} is the resonance field, and $H_k = 2K/M_s$ is the in-plane uniaxial anisotropy field. Then we can fit the in-plane angular dependent resonance field by using Eq. (4).