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Asymmetric magnetic disorder observed in thermally activated magnetization reversal of exchange-biased IrMn/CoFe films

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ABSTRACT

We report an asymmetry of magnetic disorder in exchange-biased IrMn(t_{IrMn}=5–20 nm)/CoFe(50 nm) films observed by means of a Kerr microscope, capable of direct domain observation. From the correlation between the magnetization half-reversal time and applied magnetic field, we find that the magnetization switching in all the films occurs via a thermally activated reversal mechanism for both branches of hysteresis loops. Surprisingly, in the forward branch reversal where the applied magnetic field is antiparallel to the direction of exchange-bias field, degree of magnetic disorder decreases as exchange-bias field increases, which is definitely contrasted with the case of backward branch reversal. This result is likely ascribed to the fact that the local values of exchange-bias field and coercive field are oppositely fluctuating with each other in the film.

1. Introduction

The ferromagnet (F) in contact with an antiferromagnet (AF) shows the enhancement of coercive field (H_C) and loop shift from the origin when the AF/F bilayer system is cooled down through the Néel temperature of AF, known as the exchange-bias effect [1]. Since many kinds of spin-valve structures use the exchange-biased system to pin the magnetization of F in a particular direction [2–4], elucidating the physical origin of exchange-bias effect is very important for realizing a reliable spintronic device. Recently, several studies on this issue have focused on the magnetization reversal mechanism of F layer and its asymmetric property between both branches of a hysteresis loop [5–13]. However, the underlying physics in this phenomenon is not clearly understood yet.

One of the most interesting characteristics in exchange-biased system is the increase of magnetic disorder (a degree of local variation of magnetic properties) in the F layer, since the exchange-coupling is locally varied due to interface imperfection. The disorders induce the pinning of domain wall (DW) during magnetization reversal by generating a local minimum of DW's energy. Such phenomena can play an important role on magnetization reversal behavior and its stochastic nature [14–18]. For this reason, a systematic study on degree of magnetic disorder in the exchange-biased F layer is necessary to elucidate the physical origin of the magnetization reversal mechanism and its asymmetric properties.

The first reliable experimental study on magnetic disorder in exchange-coupling system was carried out in Co/CoO films [19], where degree of magnetic disorder was tuned by controlling exchange-coupling between Co and CoO layers by controlling the temperature. However, the experiment was carried out in the system not showing a loop shift (zero exchange-bias field, $H_E=0$) but only showing an enhancement of H_C. Therefore, systematic study focusing on asymmetric property of magnetic disorder and its physical origin in exchange-biased F layer has not been reported yet. Moreover, the exchange-biased system showing loop shift with finite H_E is a good model system to investigate whether magnetic disorder acts identically or not for both branches in spite of the same structural-disordered system. In general, magnetic disorder is induced by the structural defects, for example, grain morphology, surface roughness, and nonmagnetic defects in a ferromagnetic substance [20,21]. Thus, one can naturally assume that degree of magnetic disorder should be the same in the same structural-disordered system. However, this assumption is not always correct in the exchange-biased system due to the symmetry breaking with AF layer. The existence of finite H_E implies that the local distribution of potential barriers during magnetization reversal is asymmetric between both branches of a hysteresis loop, even though structural disorders are the same.

Here, we report an asymmetry of magnetic disorder in exchange-biased IrMn/CoFe films, witnessed by means of time-resolved Kerr microscopy. The magnetization reversal in all the

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films occurs via a thermally activated reversal mechanism. Interestingly enough, difference of magnetic disorder between both branches of a hysteresis loop gradually increases with increasing IrMn thickness (t_{IrMn}).

2. Experimental details

We have prepared Si(SiO$_2$)/MgO(3 nm)/Ir$_{22}$Mn$_{78}$(t_{IrMn})/Co$_{30}$Fe$_{70}$ (50 nm) films with varying t_{IrMn} from 5 to 20 nm using a magnetron sputtering method under a base pressure of 7×10^{-9} Torr and an Ar working pressure of 3 mTorr. After the deposition, the films were annealed at 200 °C for 30 min and cooled to room temperature in an applied magnetic field ($\sim$500 Oe) to induce the exchange-bias field H_E. All the films were capped with 3-nm-thick TaN layers to prevent oxidation.

The domain images and magnetization reversal curves were measured by means of a magneto-optical microscope magnetometer (MOMM). The magnetization reversal curves were obtained by applying reversal field ($<H_C$) to an initially saturated film during 20 s. To eliminate the training effect, we measured hysteresis loop more than 20 times and then, measured magnetization reversal processes. The half-reversal time and the dispersion of activation energy barrier (degree of disorder) were obtained from the magnetization reversal curves. The magnetization reversal curves and domain images for both branches of a loop were measured at exactly the same observed area. The details of MOMM setup are described elsewhere [22].

3. Results and discussions

Fig. 1(a) and (b) shows the dependence of H_C and H_E on t_{IrMn}, respectively. It should be pointed out that H_E is gradually increased with increasing t_{IrMn}, which is contrasted with the dependence of H_C on t_{IrMn}. Such dependences are well explained in the literatures [23,24]; we will give a brief summary of them because they are closely related with our main findings. Generally, the anisotropy energy of the AF layer ($K_{AF}t_{AF}$) increases with increasing t_{IrMn}. When t_{IrMn} is less than the critical thickness, $K_{AF}t_{AF}$ is smaller than J_{INT} (the interface exchange-coupling energy between F and AF layers). In that case, AF magnetization at the interface reverses with the magnetization in the F layer, resulting in the enhancement of H_C without loop shift. However, $K_{AF}t_{AF}$ becomes dominant compared to J_{INT} as t_{IrMn} increases, resulting in the stabilization of AF magnetization at the interface, which leads to the increase of H_E and decrease of H_C.

The magnetization reversal curves were obtained for both backward and forward branches of a hysteresis loop. The backward branch indicates the reversal branch where applied magnetic field is parallel to the direction of H_E (see inset of Fig. 1(b)). Fig. 2 shows the magnetization reversal curves and their corresponding domain images. The fractional area of magnetization ($m(t)$) [12,25] that has reversed in elapsed time is defined as $(M(t)+M_S)/(2M_S)$, where $M(t)$ and M_S are the magnetization in elapsed time at the observation area and saturation magnetization, respectively. The magnetization state of domain images indicates the condition $m(t)\approx0.5$. The domain images were measured at $\times500$ magnification and their corresponding observation area is $80\times64\ \mu m^2$.

In case of backward branch reversal, the magnetization reversal occurs via DW motion for all t_{IrMn} (see the domain images in Fig. 2). Note that the number of intermediate states during magnetization reversal is gradually increased with increasing t_{IrMn}, which is due to the enhanced degree of magnetic disorder as will be discussed later. This result is consistent with the previous reports [15,19] showing increased degree of disorder due to enhanced exchange-coupling between AF and F layers. However, such a behavior is definitely contrasted with the case of forward branch reversal. The number of intermediate states during magnetization reversal decreases with increasing t_{IrMn}. Especially, the magnetization reversal for the films of $t_{IrMn}=10$ and 20 nm occurs via a sudden single jump (note that there is no corresponding domain image which corresponds to the condition $m(t)\approx0.5$.). This implies that there is almost no local variation of DW's energy due to a very low degree of disorder.

It is interesting to note that the magnetization reversal behavior is apparently asymmetric in the films of $t_{IrMn}=10$ and 20 nm between backward and forward branches. Considering that measurements of reversal curves were carried out in the same observation area, we can assume that degree of structural disorder is exactly same. Thus, our experimental finding is a strong evidence of the large variation of the degree of magnetic disorder and reversal mechanism in the same structural-disordered system.

To elucidate the details of magnetization reversal mechanism, we have measured the magnetization half-reversal time (τ) with varying applied magnetic field (H) for both forward and backward branches, as shown in Fig. 3. The τ is defined as the elapsed time at which half of the magnetization in the observation area has switched [15,22]. When the magnetization reversal occurs via a single jump, we have defined τ as the magnetization switching time of the observation area. We clearly see from Fig. 3 that τ depends exponentially on H at all t_{IrMn}, indicating a thermally activated reversal behavior. When the thermally activated reversal mechanism is dominant during magnetization reversal, τ can be determined from the equation $\tau=\tau_0\exp[M_SV_A(H_C-H)/k_BT]$, where τ_0, V_A, and k_BT are characteristic switching time when $H=H_C$, activation volume and thermal energy, respectively [26–33].

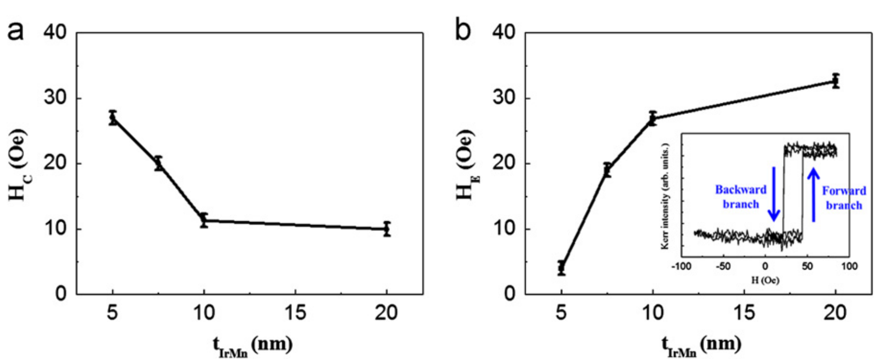

Fig. 1. Dependences of (a) the coercive field H_C and (b) the exchange-bias field H_E on IrMn thickness t_{IrMn}. The inset shows a Kerr hysteresis loop of the film for $t_{IrMn}=20$ nm. The loop shows the significant shift from the origin. The directions of backward and forward branch reversal are denoted by the arrows.