Thermal relaxation of exchange bias field in an exchange coupled CoFe/IrMn bilayer*

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This paper reports that a CoFe/IrMn bilayer was deposited by high vacuum magnetron sputtering on silicon wafer substrate; the thermal relaxation of the CoFe/IrMn bilayer is investigated by means of holding the film in a negative saturation field at various temperatures. The exchange bias decreases with increasing period of time while holding the film in a negative saturation field at a given temperature. Increasing the temperature accelerates the decrease of exchange field. The results can be explained by the quantitative model of the nucleation and growth of antiferromagnetic domains suggested by Xi H W *et al.* [2007 *Phys. Rev.* B **75** 014434], and it is believed that two energy barriers exist in the investigated temperature range.

Keywords: thermal relaxation, exchange bias, energy barrier, CoFe/IrMn bilayer
PACC: 7560, 7660E

1. Introduction

Exchange coupling at the interface between a ferromagnetic (FM) and an antiferromagnetic (AFM) layer can cause exchange biasing,[1] i.e. a shift of the hysteresis loop of the AFM layer along the field axis characterized by an exchange bias field H_{ex}. The exchange bias has been extensively studied due to its potential applications in recording media, read heads, magnetic sensors and magnetoelectronic switching devices (spin valves).[2−4]

For device applications, the long term stability of H_{ex} is an important issue. The effect of time spent in negative saturated field of the FM layer on the exchange bias has been studied.[5,6] Results indicate that H_{ex} decreases with the increase of time. On the other hand, these devices normally operate at elevated temperatures (approximately 100 °C) due to heating by the sense current.[7] Generally the exchange bias field H_{ex} decreases with the increase of temperature. Therefore, the investigation of thermal relaxation of H_{ex} is of practical importance as well as having scientific merit.

In this paper, we report on the thermal relaxation of H_{ex} by means of holding the film in its negative saturation field at various temperatures and the results are explained by the quantitative model of the nucleation and growth of AFM domains suggested by Xi *et al.*[8]

2. Experimental details

Film with a structure of Ta (5nm) / $Co_{75}Fe_{25}$ (5 nm) / $Ir_{20}Mn_{80}$ (12 nm) / Ta (8 nm) was deposited by magnetron sputtering on silicon wafer substrate with a thermally oxidized surface. The deposition conditions were: base pressure $< 5 \times 10^{-7}$ Pa, Ar sputtering pressure 7×10^{-2} Pa, deposition rate 0.03–0.12 nm/s. A magnetic field of 100 Oe (1 Oe=79.5775 A/m) was applied during sputtering of the FM and AFM layers in order to induce unidirectional magnetic anisotropy.

The magnetometry measurements were made by using a vibrating sample magnetometer (VSM) equipped with furnace attachments. The sweep-rate was kept constant at 3 Oe/s for all measurements in order to avoid different contributions from time-dependent effects. The magnetic field was applied parallel or antiparallel to the unidirectional easy axis (UEA), which coincides with the direction of the field applied during film growth. The crystal structure of the bilayer was analysed by using a D8 advance x-ray diffractometer using Cu Kα radiation.

Waiting time experiments have been undertaken at various temperatures, which are selected as room temperature (RT) (291 K), 303 K, 313 K, 323 K,

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348 K, 373 K and 398 K (below blocking temperature, $T_b = 608$ K[9]). For every selected temperature, an individual bilayer specimen is used. First, starting at a positive saturation field, the applied field was swept to a negative saturation, which saturated the FM layer in the opposite direction to its initial state. The film was then held at its negative saturation for a period of time t_{sat} at the selected temperature. Finally, the recoil loop was recorded at RT as the applied field was swept to the initial value and the forward branch of the loop was recorded without waiting at the positive saturation of the FM layer. The procedure was repeated for different values of t_{sat} so that a cumulative effect of waiting time was observed for the selected experimental temperature.

3. Results and discussion

Figure 1 shows a series of hysteresis loops for the CoFe/IrMn bilayer recorded at RT after being held in its negative saturation field for different periods of time t_{sat} at RT. For clarity, only loops corresponding to $t_{sat} = 0$, 16000 and 100000 s are shown here. One can see that as the waiting time in the negative saturation field increases, the exchange bias decreases. This phenomenon has been observed in a number of exchange coupled bilayers[5,6] and multilayers.[10]

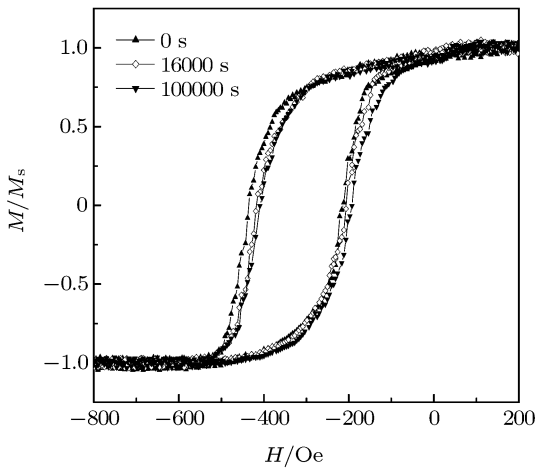


Fig. 1. Hysteresis loops for the CoFe/IrMn bilayer recorded after holding the sample in its negative saturation field for different periods of time t_{sat} at RT.

The reduction of the exchange field H_{ex} with the increase of t_{sat} is believed to be a result of the reversal of magnetization in the AFM IrMn layer driven by thermal activation over an energy barrier distribution,[5,6] which occurs as the film is held at its negative saturation. Originally the UEA of the AFM IrMn layer is parallel to the positive direction of the magnetic field and as the film is held at its negative saturation, the exchange coupling between the FM CoFe and AFM IrMn layers causes more of the domains in the AFM layer to reverse their UEA to lie parallel to the CoFe moments, i.e., antiparallel to the original UEA. This reduces the original UEA and increases the barrier to reversal along the recoil loop, resulting in a shift of the recoil loop towards zero. As the holding time increases, the degree of reversing AFM moment increases and the recoil loop shift increases. The shift of the forward loop towards zero results from the same effect that the energy barrier of the reversal of the FM CoFe layer along the forward loop decreases as the number of AFM moment antiparallel to the original UEA increases.

Figure 2 shows the normalized H_{ex} as a function of time, t_{sat}, for samples held in a negative saturation field of the FM layer at various temperatures. The exchange bias fields are normalized to the initial value of H_{ex} at $t_{sat} = 0$.

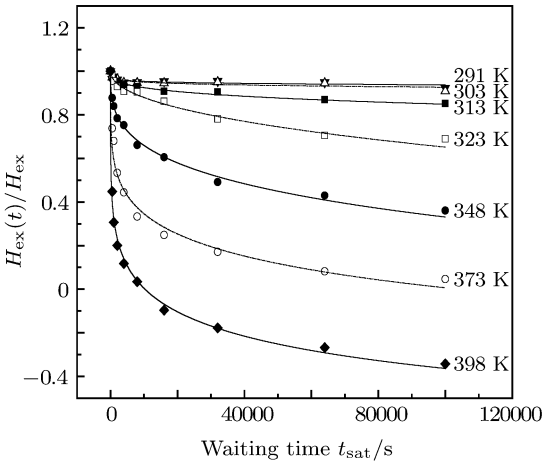


Fig. 2. Exchange bias fields measured at RT as a function of time holding the sample in a negative saturation field at various temperatures. The dots represent the experimental data and the lines represent the fits to Eq. (1).

Firstly, one can see that the exchange bias measured at RT decreases while holding the film in a negative saturation field at a given temperature. This fact is believed to result from the reversal of magnetization in the AFM layer driven by thermal activation over an energy barrier distribution as discussed for that held at RT.

Secondly, the decrease of exchange bias is most pronounced originally for each given temperature. In the AFM layer with dispersion in grain size, anisotropy, and interface coupling, smaller grains with lower energy barriers will switch faster than larger

ones with higher energy barriers due to thermal excitation.[11,12] In addition, nucleation of reversed AFM domains may appear near the sites of film defects such as voids[8] when a negative saturation field is applied. As $t_{\rm sat}$ increases, the number of unreversed smaller grains and the nucleation probability decreases. Therefore, the decrease of exchange bias field is most pronounced originally.

Finally, one can see that the rate of the thermal relaxation of the exchange bias increases with increasing temperature at which the film has been held at its negative saturation. This fact indicates that the energy barrier distribution is temperature dependent. Coherent rotation of the AFM moments is assumed to be used,[11,13,14] which means that all the spins in an AFM grain overcome the highest anisotropy energy at a same time during its process of reversal. However, if incoherent rotation occurs in an AFM grain, only some portion of the spins goes through the highest energy site at one time during the process of reversal.[15] Previous studies[11,16] show that a twisting pattern of spins may appear in the AFM layer in the process of reversal at elevated temperature. This kind of incoherent magnetic reversal of the AFM layer needs relatively lower and wider activation energy distribution than the coherent rotation of the AFM layer. Incoherent rotation is probably dominant above 348 K, which results in an enhanced thermal relaxation of exchange bias.

The decrease of $H_{\rm ex}$ as a function of time spent in a negative saturation field of the FM layer can be explained by the model suggested in Ref. [8], which quantitatively described the nucleation and domain growth behaviour of AFM grains based on the Kolmogorov–Avrami model.[17,18] For all cases, the exchange bias relaxation can be generically written as

$$H_{\rm ex}(t) = H_{\rm ex}(0)\{2\exp[-(t/\tau_{\rm D})^{\sigma}] - 1\}, \qquad (1)$$

where $\tau_{\rm D}$ is the characteristic relaxation time for the exchange bias and the power index $\sigma = 1$ for the case where the AFM domains switch independently with a constant rate, $\sigma > 1$ for the case where the reversed AFM domains nucleate with a constant rate and $0 < \sigma < 1$ for the case where the reversed AFM domains nucleate immediately after the reverse field is applied. Lines in Fig. 2 show fits of Eq. (1) to the $H_{\rm ex}(t)/H_{\rm ex}(0)$ versus $t_{\rm sat}$, which implies that the results can be explained well by the model suggested in Ref. [8].

Figure 3 shows the temperature-dependent characteristic relaxation time $\tau_{\rm D}$ obtained from the fitting. One can see that the relaxation time becomes shorter with the increase of temperature. The temperature dependence of $\tau_{\rm D}$ is well described by an Arrhenius law:

$$\tau_{\rm D} = \nu_{\sigma}^{-1}\exp(E_{\sigma}/\kappa_{\rm B}T), \qquad (2)$$

where ν_{σ} is the attempt frequency for magnetic grains, E_{σ} is the energy barrier for AFM domains to switch. This phenomenon is similar to that observed by Xi *et al.*[8] and Hughes *et al.*,[19] while two slopes exist for the $1/k_{\rm B}T$ dependence of $\ln(\tau_{\rm D})$. The slope changes at 323 K, which implies that the energy barrier may be changed in some way at this temperature. According to Eq. (2), the energy barrier E_{σ} is 6.5034 eV at the low temperature region and 0.7934 eV at the high temperature region, which indicates that the energy barrier changes with temperature. This phenomenon has also been observed by Hughes *et al.*[19]

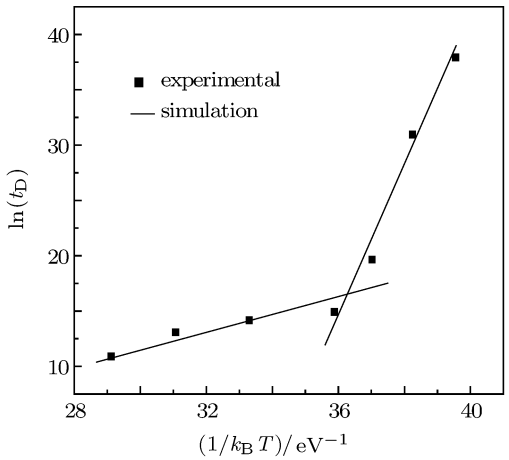


Fig. 3. Temperature dependence of the relaxation time $\tau_{\rm D}$.

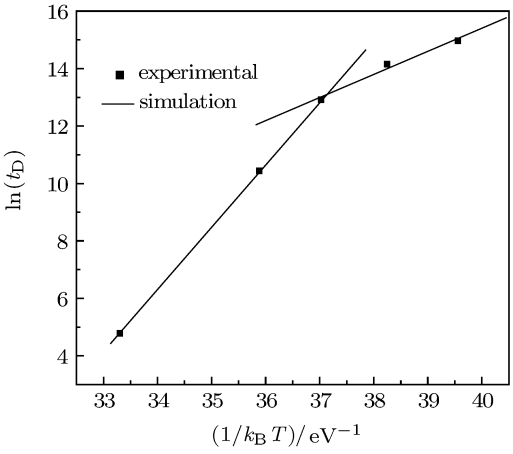


Fig. 4. Temperature dependence of the relaxation time $\tau_{\rm D}$ for $Co_{75}Fe_{25}$ (5 nm) / $Ir_{20}Mn_{80}$ (5 nm).

A similar phenomenon of two energy barriers was observed in bilayers with different AFM thickness, as shown in Fig. 4. But in $Co_{75}Fe_{25}$ (5 nm) / $Ir_{20}Mn_{80}$ (5 nm), the energy barrier changes at 313 K.

Figure 5 shows the x-ray diffraction (XRD) patterns of the bilayers, as-deposited and experienced experiments at different temperatures. One can see that the IrMn (111) peak position (corresponding to $2\theta = 41.2\ ^\circ$) remains unchanged, which indicates that the change of energy barrier cannot be attributed to the structural change of AFM domains.

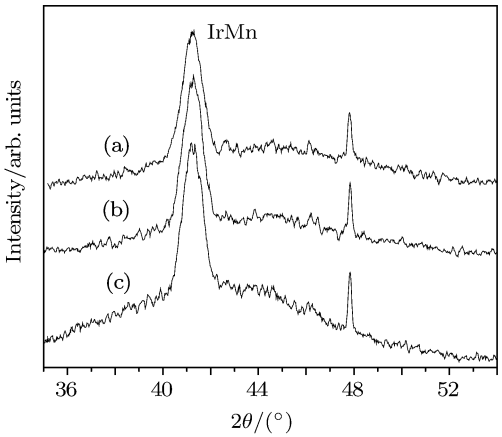


Fig. 5. The XRD patterns of the bilayers. (a) As-deposited; (b) after heating at 373 K; (c) after heating at 398 K.

The power indexes σ obtained from the fitting are shown in Fig. 6. One can see that the power index increases with temperature to a maximum at 323 K, this is consistent with the temperature at which the energy barrier changes as shown in Fig. 3, and then decreases when temperature increases further. Also, all the power indexes are between 0 and 1, which indicates that the AFM domains nucleate immediately after the reverse field is applied. The increase of the power index below 323 K results from the larger probability that the AFM domains switch independently with a constant rate at higher temperature which is due to the lower energy barrier of the switch of AFM domains as discussed above. As the temperature increases further, the nucleation sites of AFM domains increase[20] so that the probability that the AFM domains switch independently with a constant rate decreases, which results in the decrease of σ above 323 K.

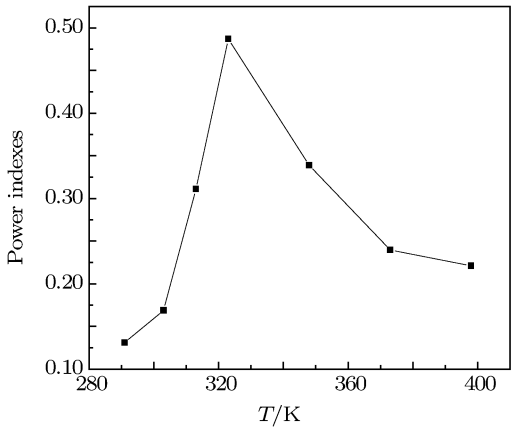


Fig. 6. The power indexes σ as a function of temperature.

4. Conclusion

In summary, the thermal relaxation of the exchange bias for the CoFe/IrMn bilayer has been studied. The exchange bias decreases with increasing period of time while holding the film in its negative saturation at a given temperature. The results can be explained well by the quantitative model of the nucleation and growth of AFM domains suggested in Ref. [8]. With the increase of temperature, the relaxation time decreases and thus the decrease of exchange field accelerates. It is believed that there exist two energy barriers in the temperature range investigated.

Ackonwledgements

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