Influence of Ga^+ ion irradiation on thermal relaxation of exchange bias field in exchange-coupled CoFe/IrMn bilayers*

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This paper reports that the CoFe/IrMn bilayers are deposited by magnetron sputtering on the surfaces of thermally-oxidized Si substrates. It investigates the thermal relaxations of both non-irradiated and Ga^+ ion irradiated CoFe/IrMn bilayers by means of holding the bilayers in a negative saturation field. The results show that exchange bias field decreases with the increase of holding time period for both non-irradiated and Ga^+ ion irradiated CoFe/IrMn bilayers. Exchange bias field is also found to be smaller upon irradiation at higher ion dose. This reduction of exchange bias field is attributed to the change of energy barrier induced by ion-radiation.

Keywords: thermal relaxation, exchange bias, ion irradiation, energy barrier

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1. Introduction

The exchange coupling at the interface between a ferromagnet (FM) and an antiferromagnet (AF) induces a unidirectional anisotropy in the FM.[1] In recent years, exchange bias has been extensively studied due to its potential applications in recording media, read heads, magnetic sensors and magnetoelectronic devices.[2−7]

Ion irradiation is an effective method of tailoring magnetism of magnetic thin films and multilayers[8,9] and thus has been used for maskless patterning of magnetic elements.[10] Variations of magnetic behaviour of magnetic thin films and multilayers have been found when they are subjected to ion irradiation. For example, in permalloy films,[11] coercivity and magnetic moment have been altered upon Cr^+ ion irradiation. In Co/Pt multilayers, ion irradiation causes the switch of magnetization direction from out-of-plane to in-plane.[12,13] Exchange biased bilayer is another system sensitive to the nature of the interface between the FM/AF layers. The effects of ion irradiation on magnetic properties of exchange-biased bilayers have also been widely reported.[14−18] The microstructures (such as grain size and texture) are significantly changed when irradiated at an ion dose over 10^{14} ions/cm^2. The mixture of elements across the interfaces between thin film and substrate occurs during irradiation and the film becomes fully amorphous when Ga^+ ion dose is sufficiently high (up to 10^{15} ions/cm^2). As a result, higher ion dose alters the reversal mechanism leading to progressive degradation of magnetic properties.

For the application of magnetoelectronic devices based on spin-valves or spin tunnel junctions, a long term stability of exchange bias subjected to maskless ion patterning is a critical issue and has been sufficiently investigated by a number of researchers.[8,9,19] Almost all these researches are focused on the reaction between primary ion beam and magnetic thin films. In fact, for the ion beam in a focused ion beam (FIB) system, a Gaussian shape with a long tail appears. Such a long tail gives rise to an artifact area during ion beam scanning. This area is essentially produced by a fairly low ion dose in comparison with primary ion beam, which may alter the magnetic properties of thin films. The aim of this paper is to clarify the influence of Ga^+ ion irradiation at low dose on the thermal relaxation of the exchange bias in CoFe/IrMn bilayers,

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which has hardly been reported.

2. Experimental details

We deposite the samples with a structure of /Seed Ta (5 nm) /$Co_{75}Fe_{25}$ (5 nm)/$Ir_{20}Mn_{80}$ (12 nm) /Cap Ta (8 nm) were deposited by magnetron sputtering on thermally-oxidized Si substrates. The deposition conditions are: base pressure $< 5 \times 10^{-7}$ Pa, Ar sputtering pressure 7×10^{-2} Pa and deposition rate 0.03–0.12 nm/s. We apply a magnetic field of 100 Oe (1 Oe = 79.5775 A/m) during sputtering of the FM and AF layers in order to induce unidirectional magnetic anisotropy. The interface roughness was performed by atomic force microscopy (AFM).

We carry out irradiation in an FEI 200TEM FIB system with 30 keV Ga^+ ions at an ion current of 1 nA. The bilayers were irradiated at ion doses of 2×10^{13} ions/cm^2 and 1×10^{14} ions/cm^2, respectively.

We investigate the thermal relaxation of CoFe/IrMn bilayers as a function of ion dose by means of holding samples in a negative saturation field of FM layer for different waiting time using a vibrating sample magnetometer at room temperature. The temperature and negative applied magnetic field used for the negative saturation were room temperature and −800 Oe, respectively. The field range of loop measurement was set to be −800 Oe ∼ +800 Oe. We keep the sweep rate of magnetic field at a constant value of 3 Oe/s in order to avoid different contributions from time-dependent effects. The magnetic field was applied parallel or antiparallel to unidirectional easy axis, which coincides with the direction of the field applied during film growth. This allows a little or no spin flop coupling between the AF and FM moments at the interface.

3. Results and discussion

As the films studied here have been grown coherently up to the expected thickness on sputtering and the AF/FM interface is not too far from the top surface, it is reasonable to think that the surface morphology is related to the interface morphology.[20]

Figure 1 shows AFM images of CoFe/IrMn bilayers irradiated with various doses. The root-mean-square roughness of the CoFe/IrMn bilayers measured from these AFM images is 0.783 nm (without ion irradiation), 0.530 nm (irradiated at a dose of 2×10^{13} ions/cm^2) and 0.485 nm (irradiated at a dose of 1×10^{14} ions/cm^2), respectively. Apparently, the roughness decreases with increasing ion dose in agreement well with the investigation by Guo *et al.*[21]

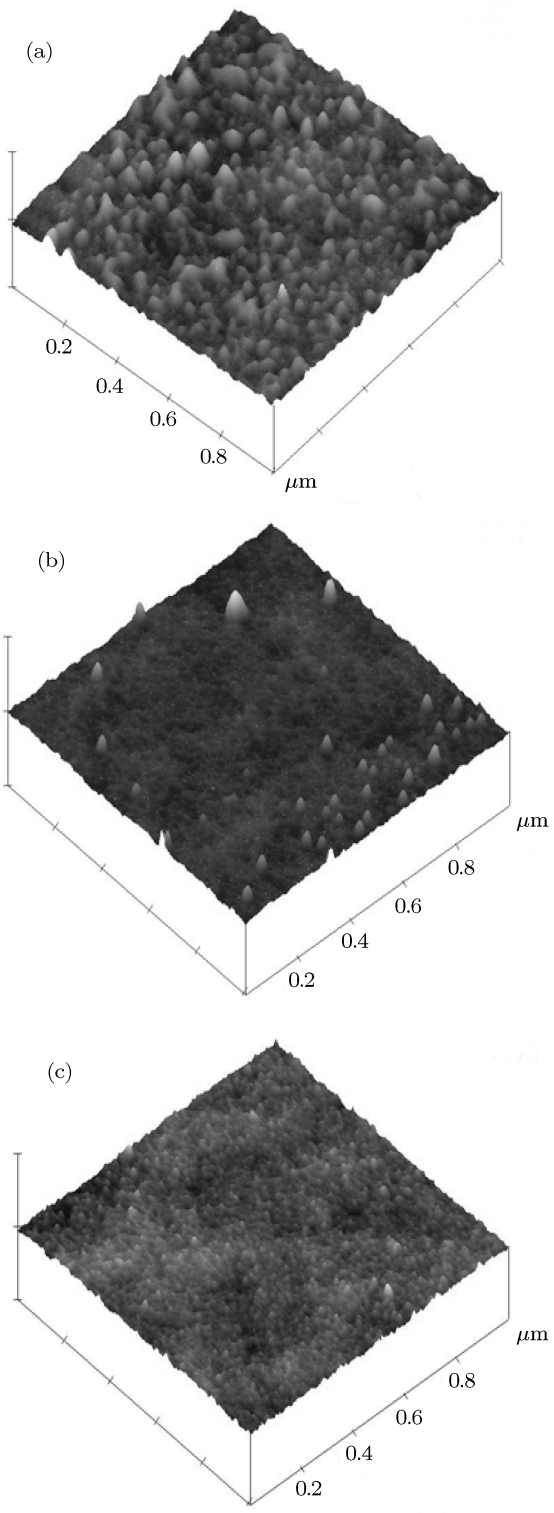


Fig. 1. The AFM images of bilayers: (a) non-irradiated; (b) Ga^+ ion irradiated with a dose of 2×10^{13} ions/cm^2; (c) Ga^+ ion irradiated with a dose of 1×10^{14} ions/cm^2.

The concentration of Ga^+ ion and Ta, Co, Fe, Mn and Ir atoms in the multilayer obtained by the stopping and ranges of ions in matter (SRIM)

simulation[22] at a dose of 1×10^{14} ions/cm^2 is shown in Fig. 2. One can see from Fig. 2(a) that the Ga^+ ions distribute mainly in IrMn layer. As shown in Fig. 2(b), the intermixing of atoms between adjacent layers is obvious and it may be responsible for the reduction of interface roughness observed by AFM measurements (shown in Fig. 1).

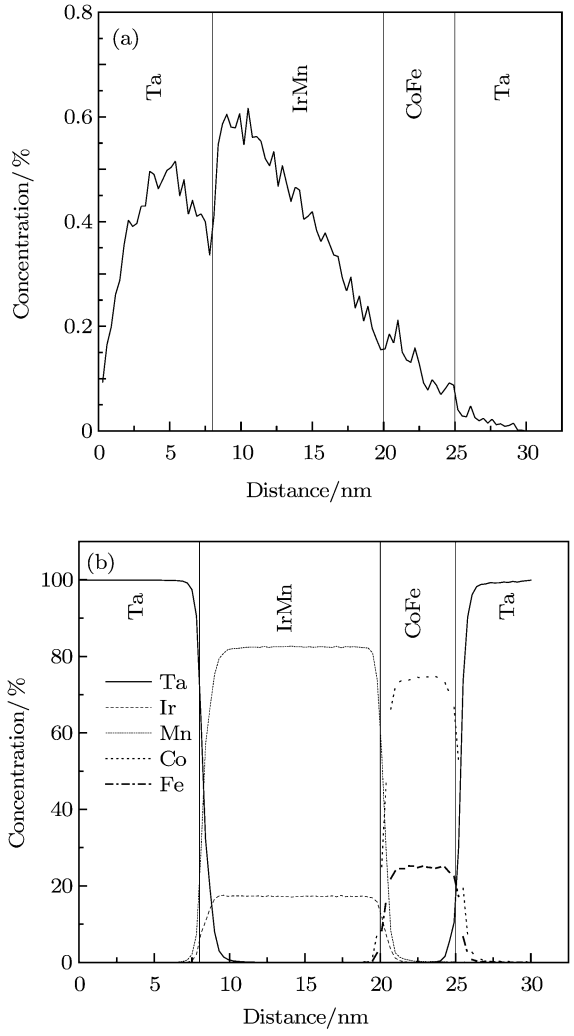


Fig. 2. Simulated concentration after irradiation at a dose of 1×10^{14} ions/cm^2: (a) Ga^+ (atomic percentage); (b) Ta, Ir, Mn, Co and Fe (atomic percentage).

The hysteresis loops of the CoFe/IrMn bilayers irradiated with various ion doses are shown in Fig. 3. It can be seen that the exchange bias field of CoFe/IrMn bilayers becomes smaller at a higher ion dose, which is consistent with the observations by McGrouther *et al.*[16] and Wang *et al.*[17] The decrease of exchange bias field is likely due to the reduction of interface roughness induced by irradiation[23] and the degradation of pinning effect of IrMn layer caused by Ga ions implantation.

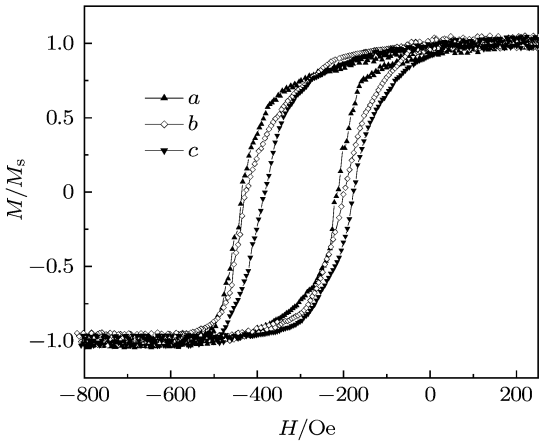


Fig. 3. Hysteresis loops of the CoFe/IrMn bilayers: curve a non-irradiated (H_{ex}: 324 Oe). curve b Ga^+ ion irradiated with a dose of 2×10^{13} ions/cm^2 (H_{ex}: 313 Oe); curve c Ga^+ ion irradiated with a dose of 1×10^{14} ions/cm^2(H_{ex}: 280 Oe).

Figure 4 shows hysteresis loops collected after samples being held in the negative saturation field of FM layer for three different periods of time (i.e. $t_{sat} = 0$, 16000 and 100000 s), for the non-irradiated bilayers and irradiated bilayers with various ion doses. It shows that the exchange bias field of each bilayer goes down with the increase of waiting time. This time-dependent effect has been found in CoFe/IrMn bilayers[24,25] and other exchange coupled bilayers[26] by some researchers. The reduction of the exchange bias field H_{ex} with increasing t_{sat} is believed to be a result of the reversal of magnetization in the AF IrMn layer driven by thermal activation over an energy barrier distribution,[24,25,27,28] which occurs when the film is held in negative saturation field. The exchange coupling between FM/AF layers causes more spins within the AF layer to rotate antiparallelly to the unidirectional easy axis when waiting time is longer. As a result, original unidirectional anisotropy reduces and this fact leads to the decrease of the exchange field.

Figure 5 shows the normalized H_{ex} as a function of time, t_{sat}, for samples irradiated with various doses. It should be noted that the exchange bias fields are normalized to the initial value of H_{ex} at $t_{sat} = 0$. It is seen that exchange bias decreases rapidly at the beginning. This is due to the reversal of AF domains with small grains. These domains with small grains have low energy barriers, which enable magnetization to be switched easier than domains with large grains having high energy barriers caused by thermal excitation.[29] In addition, reversed AF magnetic domains, in general, are nucleated at those sites near film defects such as voids[30] when a negative saturation field is applied. As t_{sat} increases, the number of un-reversed domains with smaller grains and the nucleation probability de-

creases.

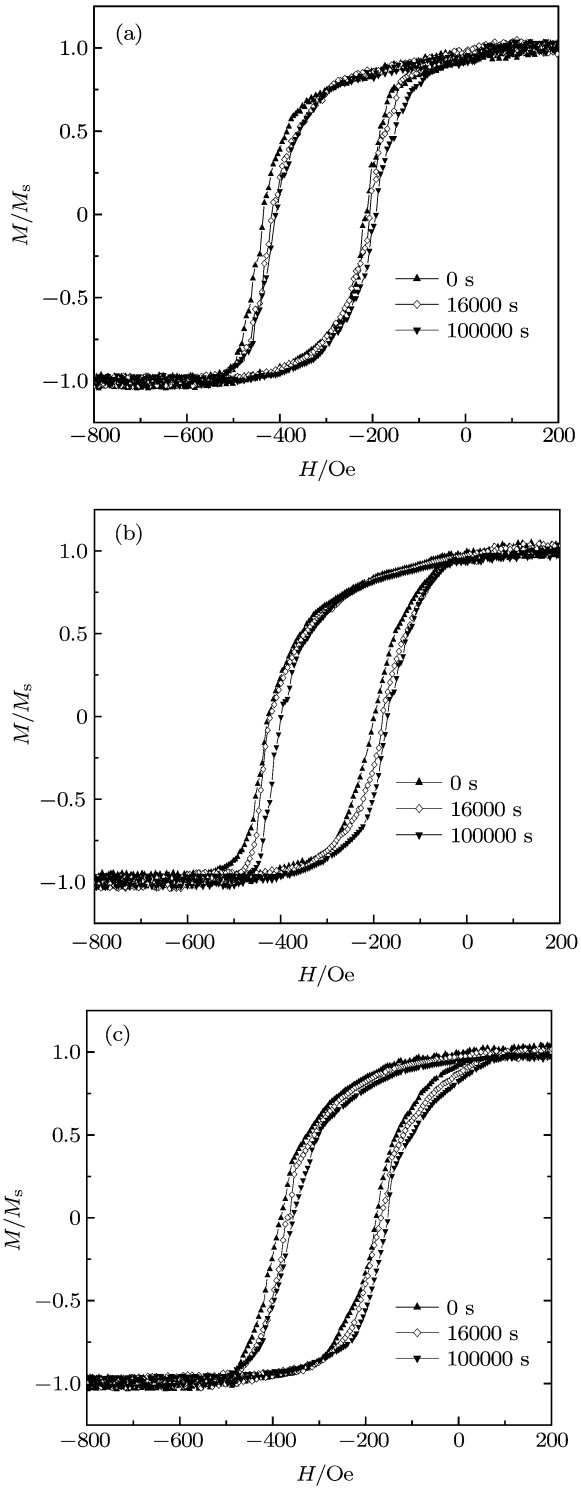


Fig. 4. Hysteresis loops for the CoFe/IrMn bilayer held at a negative saturation field of the pinned FM layer for different periods of time: (a) non-irradiated; (b) Ga^+ ion irradiated with a dose of 2×10^{13} ions/cm^2; (c) Ga^+ ion irradiated with a dose of 1×10^{14} ions/cm^2.

Furthermore, Fig. 5 shows that exchange bias field decreases rapidly with the increase of ion dose, indicating that the energy barrier distribution is dose-dependent. We shall discuss this in more detail below.

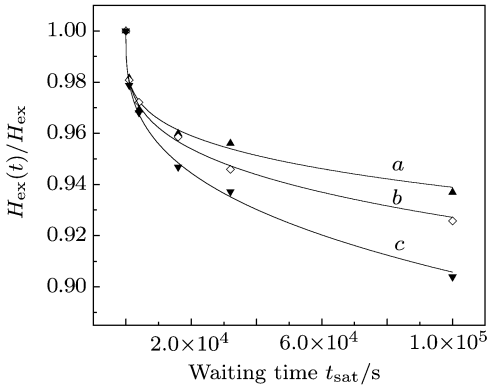


Fig. 5. Exchange bias fields as a function of time while holding the sample in a negative saturation field with various doses. The dots represent the experimental data and the lines fitting to Eq. (1): curve a non-irradiated; curve b Ga^+ ion irradiated with a dose of 2×10^{13} ions/cm^2; curve c Ga^+ ion irradiated with a dose of 1×10^{14} ions/cm^2.

The decrease of H_{ex} as a function of waiting time in the negative saturation field of the FM layer can be explained by a model proposed by Xi *et al.*[30] This model, established based on the Kolmogorov–Avrami model, describes the nucleation and growth behaviour of AF domains quantitatively. In normal case, exchange bias relaxation can be generically written as

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

where τ_D is the characteristic relaxation time for the exchange bias, which can give a quantitative description of thermal stability. Higher τ_D represents better thermal stability. The power index $\sigma = 1$ for the case where the AF domains switch independently with a constant rate, $\sigma > 1$ for the case where the reversed AF domains nucleate with a constant rate and $0 < \sigma < 1$ for the case where the reversed AF domains nucleate immediately after the reverse field is applied.

Dividing Eq. (1) by $H_{ex}(0)$ on both sides, we obtain,

$$\frac{H_{ex}(t)}{H_{ex}(0)} = 2\exp[-(t/\tau_D)^\sigma] - 1 \qquad (2)$$

which is a function of $H_{ex}(t)/H_{ex}(0)$ against t_{sat}. It is found that this function fits those curves in Fig. 5 very well. This suggests that our results follow the model proposed by Xi *et al.*[30]

The power index σ in the paper is obtained by the fitting of experimental data with Eq. (2). The values of σ are 0.25, 0.30, and 0.33 for non-irradiated bilayer and two ion irradiated bilayers with doses of 2×10^{13} and 1×10^{14} ions/cm^2, respectively. All the power indexes are between 0 and 1. This fact indicates that the AF domains nucleate immediately after the

reverse field is applied. The created defects induced by ion irradiation reduce the domain size in the AF layer, decrease the energy barrier of the switch of AF domains, i.e., AF domains reverse easier after ion irradiation. So it is concluded that the increase of the power index with increasing ion dose results from the larger probability that the AF domains switch independently with a constant rate at higher ion dose.

In addition, the relaxation time $\tau_{\rm D}$ obtained from curve fitting is 7.88×10^{10}, 5.59×10^{9}, and 9.68×10^{8} s, for non-irradiation bilayer and bilayer samples irradiated at two ion doses of 2×10^{13} and 1×10^{14} ions/cm^2, respectively. It decreases with the increase of ion doses, suggesting that the thermal stability of exchange bias field decreases.

Created defects induced by ion irradiation reduce the domain size in the AF layer, decreasing the energy barrier of the switch of AF domains. This analysis is consistent with the Arrhenius law $\tau_{\rm D} = \nu_\sigma^{-1}\exp(E_\sigma/\kappa_{\rm B}T)$ ($\tau_{\rm D}$: relaxation time, ν_σ: attempt frequency, E_σ: energy barrier). Consequently, we can conclude that the rapid reduction of exchange bias field with increasing ion dose is due to the decrease of energy barrier with the increase of ion dose.

4. Conclusion

In this paper, the thermal relaxation of the exchange bias field for the CoFe/IrMn bilayer has been studied. Irradiation induces the decrease of the interface roughness hence leading to the reduction of exchange bias field. The exchange bias fields of irradiated and non-irradiated bilayers decrease with the increase of the holding period of time in a negative saturation field. The reduction of the relaxation time of the exchange bias field with increasing ion dose is attributed to ion irradiation, which lowers the energy barrier for the switch of AF domains.

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