Influence of Ga^+ ion irradiation on the magnetisation reversal process and magnetoresistance in CoFe/Cu/CoFe/IrMn spin valves*

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(Received 30 June 2009; revised manuscript received 11 October 2009)

Ga^+ ion irradiation is performed on the surfaces of IrMn-based spin valves and the effects of ion irradiation on the magnetisation reversal process and magnetoresistance (MR) are investigated. The results show that the exchange bias field and magnetoresistance ratio of the spin valve decrease with the increase of ion dose. The width of the forward step between the free layer and the pinned layer becomes gradually smaller with the increase of ion dose whilst the recoil step tends to be narrower with ion dose increasing up to 6×10^{13} ions/cm^2 and the step disappears afterwards. Two peaks in the *R–H* curve are found to be asymmetric.

Keywords: ion irradiation, magnetisation reversal, magnetoresistance, exchange bias
PACC: 7570P, 7560

1. Introduction

Recently, it has been demonstrated that ion irradiation can be used as an excellent tool to modify the magnetic properties of thin films without affecting their topography.[1,2] Depending on the ion mass, its energy, and the dosage, ion irradiation induces displacement cascades, resulting in atomic diffusion, the modification of crystal structures, and the alteration of grain size.[3−9] The effects of ion irradiation on magnetic properties of exchange coupling multilayers have been widely reported.[1,4,10,11] In the case of a ferromagnetic/antiferromagnetic (FM/AF) exchange coupling multilayer, the exchange bias field is sensitive to the interface and the AF anisotropic energy.[12,13] The exchange field can be either enhanced by the creation of defects, acting as domain-wall pinning sites, or suppressed to zero by the intermixing.[14,15] For example, in CoFe/IrMn exchange coupled bilayers,[4] ion irradiation induces intermixing of atoms between the various layers, leading to the change of magnetic property.

In fact, the ion beam in a focused ion beam (FIB) system appears to be of Gaussian shape with a long tail. Such a long tail gives rise to an artefact area during ion beam scanning. This area is produced by a fairly low ion dose in comparison with the primary ion beam, which may change the magnetic properties of thin films. A schematic diagram illustrating this process is shown in Fig. 1.

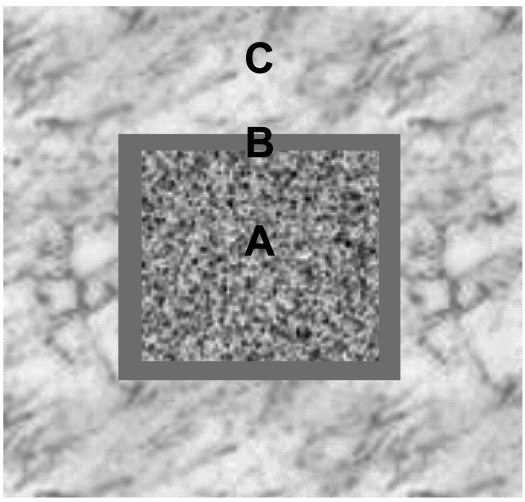


Fig. 1. A schematic diagram showing an area after irradiation by ion beam (not scaled): (A) irradiation area selected for ion beam scanning, (B) artefact area caused by the Gaussian tail of the ion beam, (C) unirradiated area.

The influence of ion irradiation on the exchange

*Project supported by the National Natural Science Foundation of China (Grant No. 50671048).
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bias field has been extensively studied.[1,4,11,13,15,16] It is generally believed that[15,16] ion irradiation has been used to change both the magnitude and direction of the exchange field. However, the influence of ion irradiation on the magnetisation reversal process is still not clear. In the present work, we report on the influence of Ga^+ ion irradiation at low dose on the magnetisation reversal process and magnetoresistance in CoFe/Cu/CoFe/IrMn spin valves.

2. Experimental details

The top spin valves with a structure of /Seed Ta (5 nm) / $Co_{75}Fe_{25}$ (5 nm) / Cu (2.5 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 as follows: base pressure $< 5 \times 10^{-7}$ Pa, Ar sputtering pressure 7×10^{-2} Pa and 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 AF layers in order to induce unidirectional magnetic anisotropy.

Irradiation was performed in an FEI 200TEM FIB system with 30 keV Ga^+ ions by using an ion beam current of 1 nA. The stacks were irradiated by ion beams with doses, separately, at 1×10^{13} ions/cm^2, 6×10^{13} ions/cm^2, 3×10^{14} ions/cm^2.

The crystal structure was analysed by using an x-ray diffractometer (D8 advance) with Cu-Kα radiation ($\lambda = 0.15405$ nm). Magnetic resistance was measured by a standard linear four point method in which the in-plane current was applied. The interface roughness was investigated by atomic force microscopy (AFM).

The magnetic properties of the spin valve structures were investigated by using a vibrating sample magnetometer at room temperature. The field range of loop measurement was set to be −800 Oe–+800 Oe. The sweep rate of magnetic field was kept constant (at 3 Oe/s) in order to avoid different contributions from time-dependent effects. The magnetic field was applied in the direction parallel or antiparallel to the unidirectional easy axis, which coincides with the direction of the field applied during film growth. This allows little or no spin flop coupling between the AF and FM moments at the interface.

3. Results and discussion

Figure 2 shows a series of the hysteresis loops of the CoFe/Cu/CoFe/IrMn spin valves irradiated by the ion beam with various ion doses. Firstly, the exchange bias field (H_{ex}) is seen to decrease with the increase of ion dose, which is in agreement with the observations of CoFe/IrMn exchange-coupled bilayers[4,11] and NiFe/CoFe/Cu/CoFe/IrMn spin valves.[10] Successive increase of ion dose leads to an enhanced amount of interface intermixing that reduces the exchange coupling.[17,18] Thus, the reduction of exchange bias field is attributed to an increased interface intermixing. Secondly, the loop of the free CoFe layer (F_f) becomes broadened with the increase of ion dose, indicating that a higher ion dose gives rise to a bigger coercivity (H_c) of the free CoFe layer.

It is believed that this enhancement is due to the generation of defects that cause more pinning sites in the layer[19,20] and the change of the exchange coupling between the free layer and the pinned layer induced by ion irradiation. In contrast, the loops of the pinned CoFe layer (F_p) become narrow, leading to a lower coercivity, which decreases against Ga^+ ion doses. This result is consistent with that in Ref. [4]. Finally, as shown in Fig. 2, the width of the forward step between the free layer and the pinned layer becomes gradually smaller with increasing ion dose whilst the recoil step tends to be narrow with ion dose increasing up to 6×10^{13} ions/cm^2 and the step disappears afterwards. This outcome can be attributed to the decrease of exchange coupling caused by ion irradiation.

The R–H curves of spin valves with and without Ga^+ ion irradiation measured at room temperature are shown in Fig. 3. The maximum resistance (R_{max}) of spin valves shows a maximum at a dose of 6×10^{13} ions/cm^2. This is believed to result from competition between two phenomena caused by Ga^+ ion irradiation. One is that the ion irradiation causes more defects which lead to the increase of spin scattering, and thus resistance increases, which is in agreement with the measurement by Kerr *et al.*[10] The other is that ion irradiation increases the ferromagnetic coupling between the F_f and F_p layers, inducing a large coercivity of F_f, which leads to an enhanced restriction of the field regime with antiparallel magnetisation, thereby reducing the R_{max} at the elevated dose. In addition, as shown in Fig. 4, the magnetoresistance ratio $(R_{max} - R_{min})/R_{min}$ is found to decrease with the increase of ion doses, which is consistent with that reported by Guo *et al.*[21] and Kerr *et al.*[10]

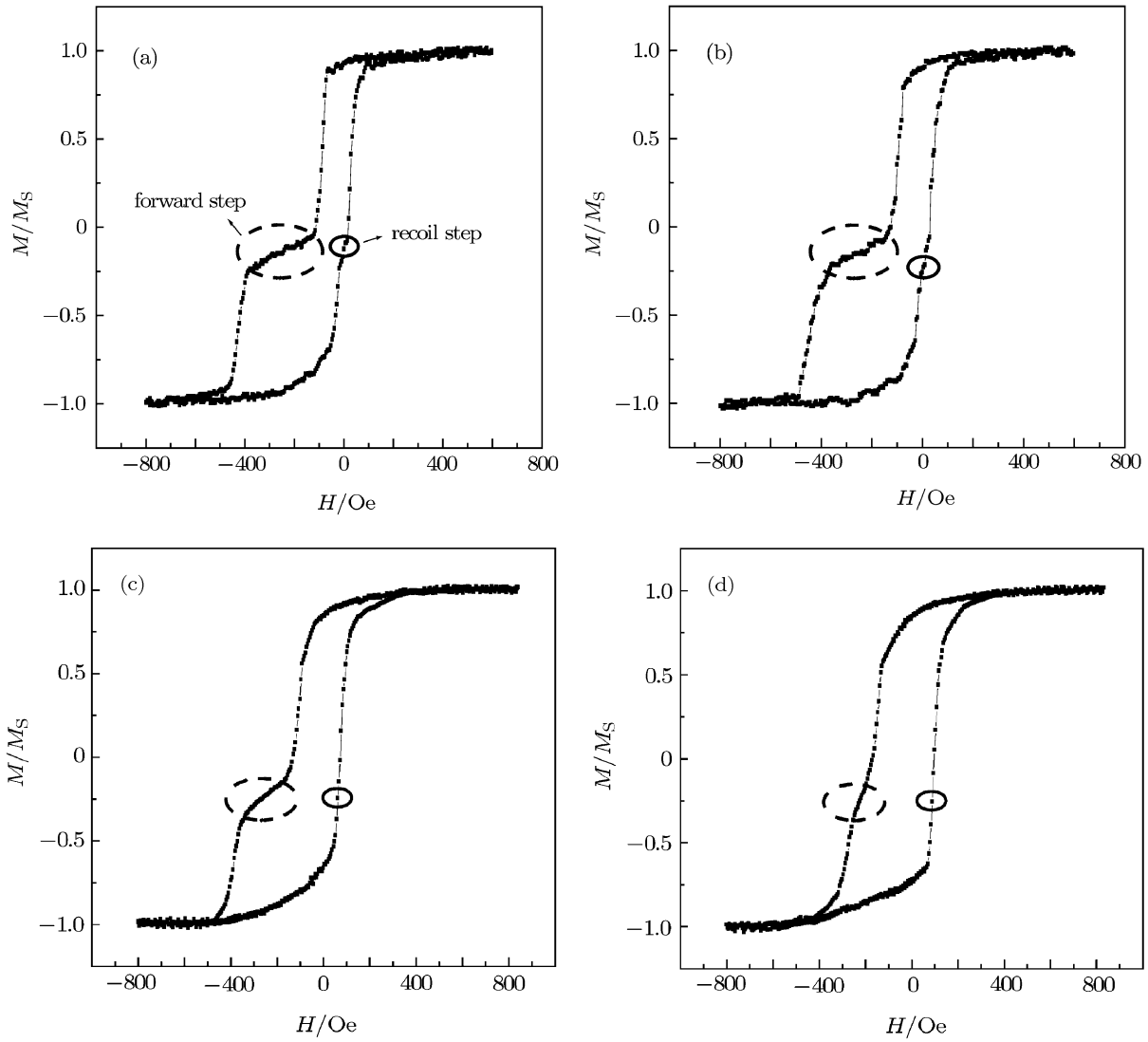
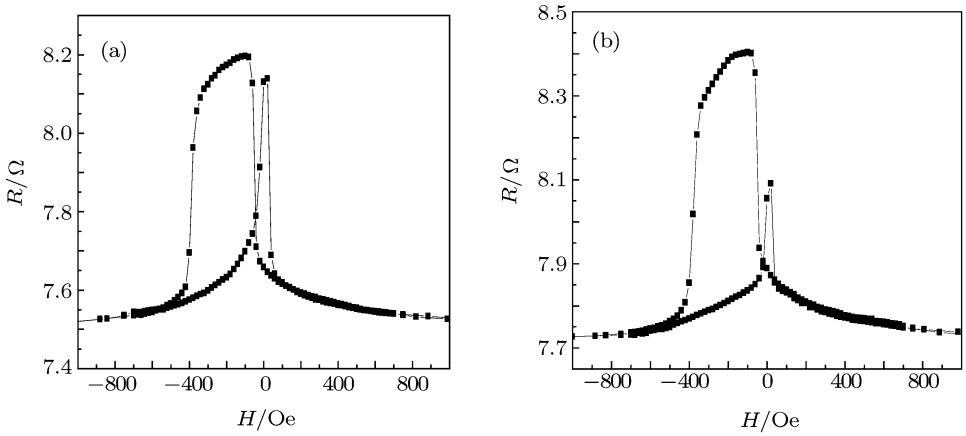


Fig. 2. Hysteresis loops of the spin valves without Ga^+ ion beam irradiation (curve *a*) and with Ga^+ ion beam irradiation at a dose of 1×10^{13} (b), 6×10^{13} (c), and 3×10^{14} ions/cm^2 (d).



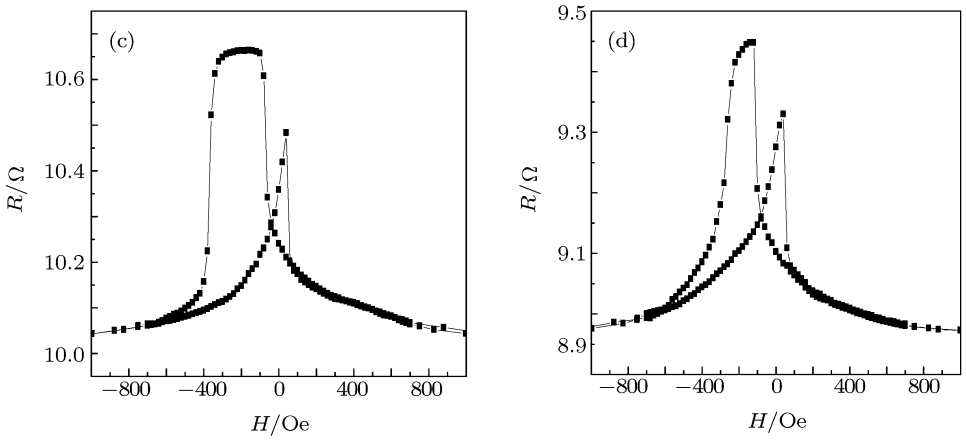


Fig. 3. *R–H* curves of spin valves measured at room temperature without Ga^+ ion beam irradiation (a), and with Ga^+ ion beam irradiation at a dose of $1.\times10^{13}$ (b), $6.\times10^{13}$ (c), and $3.\times10^{14}$ ions/cm^2 (d).

Furthermore, it is noted that the two peaks in the *R–H* curve are asymmetric. This is believed to be a result of the asymmetric steps on the forward and the recoil branches of the hysteresis curves.[22] Owing to the small exchange bias field, the difference in magnetisation direction between the F_f layer and the F_p layer on the recoil branch is smaller than that on the forward branches (180°).

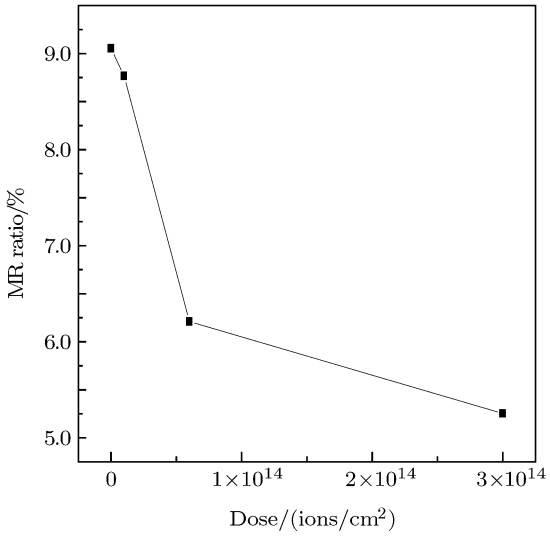


Fig. 4. MR ratio as a function of ion dose.

In order to confirm these physical changes induced by ion irradiation, x-ray diffraction and AFM measurement were carried out. As seen in Fig. 5, all diffraction patterns show fcc structure with ⟨111⟩ crystallographic texture and the peak position corresponding to IrMn (111) crystallographic plane shifts towards the high-angle region and the degree of texture decreases with the increase of Ga^+ ion dose. It is believed that the degradation of texture reduces exchange bias field[16,23] and MR ratio.[16] Figure 6 shows AFM images of spin valves irradiated with various doses. The magnitudes of root-mean-square roughness of the spin valves measured from these AFM images are 0.678 nm (without ion irradiation), 0.830 nm (irradiated at a dose of 1×10^{13} ions/cm^2), 0.749 nm (irradiated at a dose of 6×10^{13} ions/cm^2) and 0.466 nm (irradiated at a dose of 3×10^{14} ions/cm^2). From these data, it is found that the roughness of the thin film increases initially with the increase of ion dose to 1×10^{13} ions/cm^2 and then reduces when a larger ion dose is applied. The reason

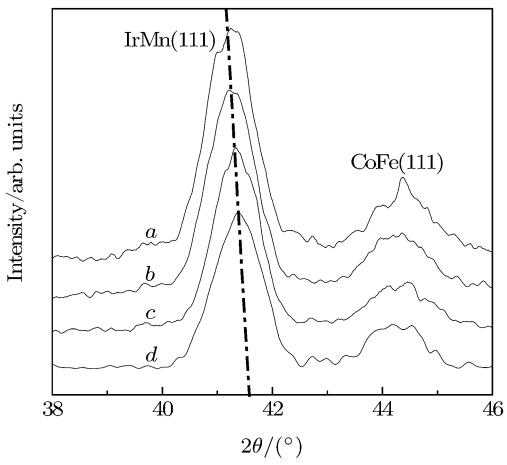


Fig. 5. X-ray diffraction patterns of spin valves without Ga^+ ion beam irradiation (curve *a*), and with Ga^+ ion beam irradiation at a dose of $1.\times10^{13}$ (curve *b*), $6.\times10^{13}$ (curve *c*), and $3.\times10^{14}$ ions/cm^2 (curve *d*).

for this is that when the film is irradiated, two phenomena appear: grain growth[24,25] and intermixing of atoms.[4,19] Grain growth leads the interface roughness to increase while intermixing of atoms causes it to decrease. The competition between the grain growth and the intermixing of atoms results in the dependence of interface roughness on ion dose. It is well demonstrated that roughness enhances MR.[26] However, from our observations shown in Fig. 4, MR ratio decreases monotonically with the increase of ion dose, which indicates that the change of texture plays a dominant role in the case of lower dose.

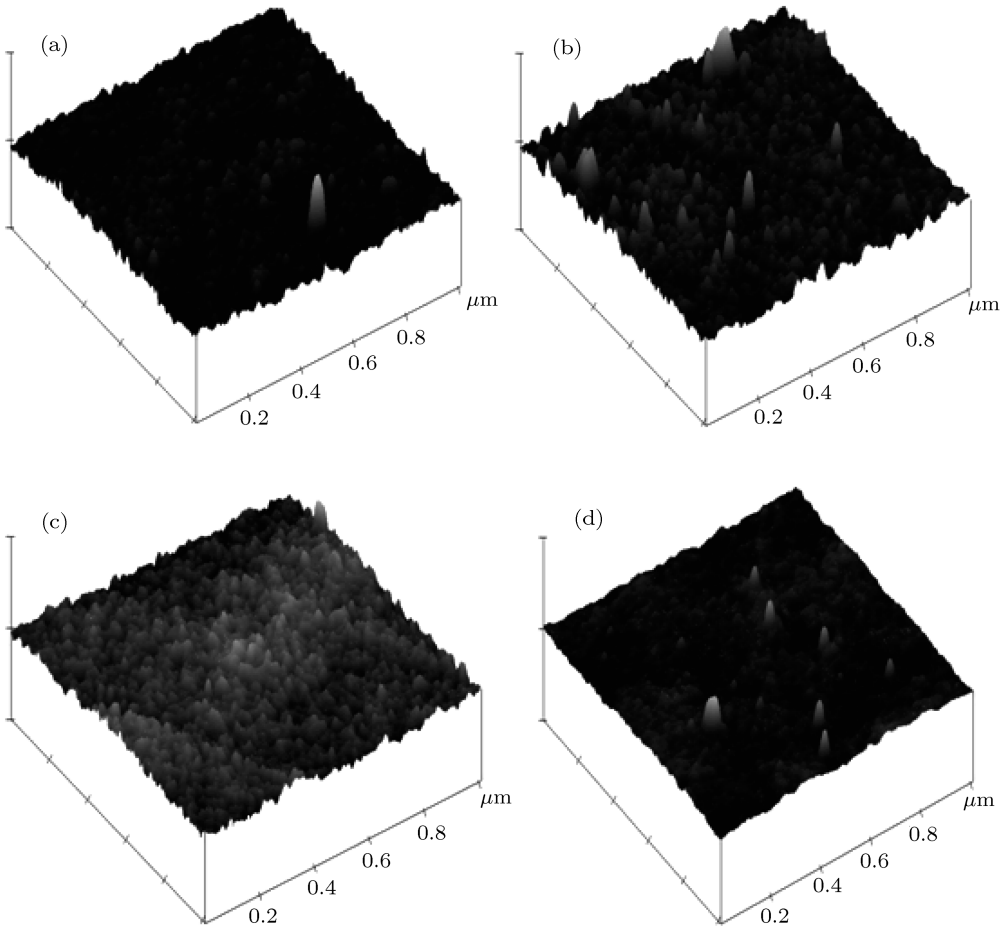


Fig. 6. AFM images of spin valves without Ga^+ ion beam irradiation (a), and with Ga^+ ion beam irradiation at a dose of $1.\times10^{13}$ (b), $6.\times10^{13}$ (c), and $3.\times10^{14}$ ions/cm^2 (d).

4. Conclusions

Ion irradiation of CoFe/Cu/CoFe/IrMn top spin valves by using a focused beam of 30 keV Ga^+ ions is carried out. The results show that the exchange bias field and magnetoresistance of the spin valve decrease with the increase of ion dose. Such a reduction for both exchange bias and MR ratio can be attributed to the microstructural modification induced by Ga^+ ion irradiation. Owing to the small exchange bias field, the difference in magnetisation direction between the F_f layer and the F_p layer on the recoil branch is smaller than that on the forward branch (180°), which is responsible for the asymmetry of two peaks in the R–H curve.

Acknowledgement

The authors would like to thank Professor Han Xiu-Feng at the Institute of Physics, Chinese Academy of Sciences, for supporting the preparation of the specimens.

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