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Defect induced enhancement of exchange bias by swift heavy ion irradiation in zinc ferrite–FeNiMoB alloy based bilayer films

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ABSTRACT

Exchange biased systems consisting of ferromagnetic (FM)–antiferromagnetic (AFM) interfaces are increasingly being investigated because of their application potential in spin valves and tunnel junctions. In bilayer systems, ion irradiation is capable of modifying the interface and thereby offers unique opportunities to tailor exchange field. In the present study, irradiation with 100 MeV Ag^{8+} ions is utilized to alter the exchange bias field in zinc ferrite–FeNiMoB bilayer system. The thin films which were deposited by RF sputtering technique and annealed at 600 °C were irradiated at various fluences. Structural and magnetic studies were carried out by using Glancing X Ray Diffractometer (GXRD) and Superconducting Quantum Interference Device Vibrating Sample Magnetometer (SQUID VSM) respectively. It was observed that the as deposited films exhibited exchange bias and on ion irradiation, bias field could be enhanced at certain fluences. The enhancement in bias field is attributed to defects created in the antiferromagnet as a result of ion irradiation. The experimental result is fitted in accordance with the diluted antiferromagnet model. Coercivity was also found to vary with ion fluence. Ion fluence was thus effectively used to enhance bias field as well as coercivity in the bilayer consisting of zinc ferrite–FeNiMoB.

1. Introduction

The phenomenon of exchange bias attracted scientists and engineers alike owing to the richness in physics and also due to its technological applications [1] ever since its discovery by Meiklejohn and Bean in 1956 [2]. At the ferromagnet (FM)–antiferromagnet (AFM) interface, the spins of the ferromagnet are pinned by the antiferromagnet on field cooling below the Neel temperature of the AFM. The main indications of exchange bias are a hysteresis loop shift along the field axis, widening and symmetry loss of the loop and also a vertical shift in magnetisation [1]. The FM–AFM interface plays a dominant role in determining the exchange bias properties. Though, in principle, any FM–AFM interface can exhibit exchange bias effects, thin film forms of these systems are a pre-requisite for applications [3]. Such FM–AFM interfaces are a key to their operation of functional devices such as magnetic tunnel junctions, storage units and spin valves [1,4]. Applications involving exchange bias necessitate tailoring bias and coercive fields by appropriate techniques [5]. The bias field and coercive field can be varied by varying film thickness, growth conditions and by a judicious choice of materials. Since exchange bias is an interface phenomenon, introducing defects or disorder at the interfaces modifies the exchange bias and can be explained using the diluted AFM model proposed by Miltenyi et al. [6]. In their study, they observed that defects favour formation of domains which control exchange bias. This theory was a proof for the domain state model proposed by Mauri et al. [7].

Many researchers have observed that the bias and coercive fields are greatly influenced by both the FM and AFM thickness [8–11]. The most well studied exchange bias system is FeNi–FeMn. In this system it was reported that the bias field obeys a power law with AFM thickness as $1/t^{\lambda}$, where the exponent λ ranges from 0 to 0.3 [11]. The inverse relation of exchange bias with AFM thickness was also observed in various other systems namely $IrMn_3/Co$, $La_{2/3}Ca_{1/3}MnO_3/La_{1/3}Ca_{2/3}MnO_3$, Ta/Py/IrMn/Pt

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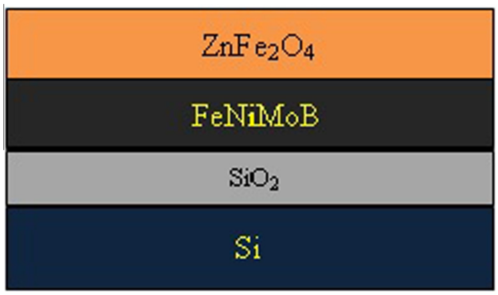

Fig. 1. Schematic of the bilayer structure.

[9,10,12]. In most of the studies carried out so far, the optimum thickness of the AFM layer is ~20 nm, the bias field disappears for thickness values greater than this optimum thickness [12–15]. In some other systems like Cu–Mn–Co, it was observed that bias field increases with thickness and attains saturation [16,17]. The effect of thickness on the exchange bias is not universal and found to vary from system to system. Apart from FM-AFM interfaces, FM–Spin Glass (SG) systems are also found to exhibit exchange bias [16]. Recent reports suggest that the dependence of bias field on film thickness and cooling field in FM–SG layers are similar to those observed in FM–AFM systems [16,17]. In FM–SG systems the spin glass is modeled as a diluted AFM with long range interactions [17].

Ion irradiation offers unique possibilities in modifying exchange bias [1]. The ions can interact with the material in two ways: by elastic collision with nuclei which is termed as nuclear energy loss and by inelastic collisions with electrons termed as electronic energy loss. The nuclear energy loss is predominant at lower energies (~keV range) while electronic energy loss dominates at higher energies (MeV range). Swift heavy ions are of the order of MeV energies and the ions lose energy predominantly by electronic energy loss [18]. The interaction of swift heavy ions can be explained by the thermal spike model [19]. The passage of heavy ions creates a high temperature region within the material, which is accompanied by a sudden cooling. This facilitates formation of amorphous tracks or recrystallisation in the material. The defects created by the passage of ions act as pinning centers leading to the formation of domain walls, which enhances the field shift. In the case of bilayer films, ions mix at the interface leading to broken exchange interactions which in turn suppress exchange bias. The observed change in exchange bias with ion fluence has been modeled based on a competition between defect creation and interfacial mixing [20]. Most of the ion induced modification studies on exchange bias systems are found in the low energy regime [13,14,20–25]. Mougin et al. studied the effect of 10 keV He ions on 5–10 nm FeNi–FeMn thin films [14]. They observed an enhancement of exchange bias at lower fluences and decrease at higher fluence. Schmalhorst et al. have studied the influence of ion bombardment in transport and exchange bias properties of magnetic tunnel junctions. They observed that by ion bombardment in the presence of a magnetic field exchange bias can be initiated without field cooling [22]. Engel et al. modified the model proposed by Mougin [21,23]. Ehresmann et al. theoretically and experimentally verified the role of multi domains and its modification by ion bombardment in the exchange bias properties. According to his model the ion bombardment causes a localized hyper thermal heating and this causes a time dependent variation of exchange bias after ion bombardment [24]. Later they modeled this time dependent exchange bias as a logarithmic increase in exchange bias with time [25]. Effect of keV ion irradiation in exchange bias is well studied both theoretically and experimentally, studies on modification of exchange bias by swift heavy ion irradiation are rare. It must be noted here that low energy ions are suitable for modification of materials when the film thickness is small (~1–10 nm). For larger film thickness (~100–1000 nm) the less energetic ions get embedded in the film; however, high energy ions create amorphous tracks in films of much larger thickness. As mentioned earlier, the dominant mechanism of material modification at low energies is via nuclear energy loss, while in the case of high energy ions it is through electronic energy loss and hence effect of high energy ions on exchange bias properties is also interesting from a fundamental perspective. Effect of high energy ions on the exchange bias properties would be an interesting research area since it offers an ideal template to investigate the effect of electronic energy loss on exchange bias properties. It is interesting to check weather exchange bias modification follows the same behavior at higher energies as that at lower energies.

The system under investigation is zinc ferrite–metallic glass. Zinc ferrite is an antiferromagnet with a Neel temperature of 10 K, while metallic glass, an alloy of Fe, Ni, Mo, B is an excellent soft ferromagnetic material with a Curie temperature of 600 K. Zinc ferrite in the nano regime is purported to be exhibiting anomalous magnetic behavior like ferrimagnetic, superparamagnetic, antiferromagnetic or even glassy behavior depending on cation distribution in the A and B sites of the spinel structure [27–32]. Hysen et al. and Senoy et al. reported good soft magnetic properties in thin films of Fe–Ni alloys and the properties could be tailored by thermal annealing and swift heavy ion irradiation [33–35]. Substantial amount of work has been carried out in the past on these materials namely, zinc ferrite and Fe–Ni alloys in the author's laboratory,[31–35] and it was thought fit to look at the possibilities of inducing exchange bias on a bilayer consisting of zinc ferrite and Fe–Ni alloys fabricated using RF sputtering. The effect of swift heavy ion irradiation on the exchange bias field and coercivity is of interest to the scientific community and is one of the motives of the present investigation.

2. Experimental details

The bilayer film of zinc ferrite–FeNiMoB was prepared by RF sputtering by using targets of FeNiMoB ribbon and zinc ferrite target prepared by sol gel auto combustion technique. The films were deposited on naturally oxidized Si substrate. The schematic of film is given in Fig. 1. The as deposited films annealed at 600 °C were subjected to swift heavy ion irradiation employing 100 MeV Ag^{8+} ions at fluences of 1×10^{11}, 1×10^{12}, 1×10^{13} and 3×10^{13} ions/cm^2. The experiment was carried out using 15 UD

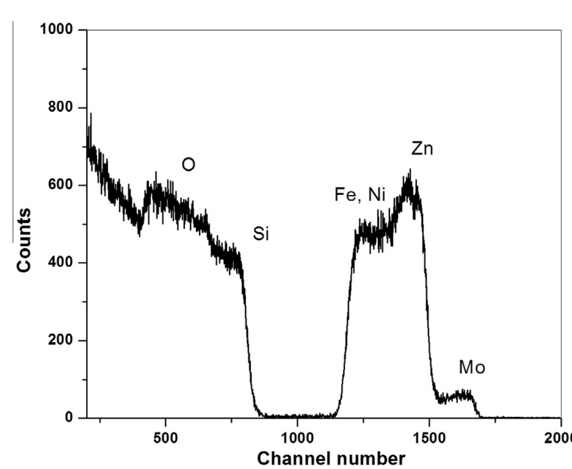

Fig. 2. RBS spectra of film annealed at 600 °C.