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Study of angular dependence of exchange bias and misalignment in uniaxial and unidirectional anisotropy in NiFe(111)/FeMn(111)/CoFeB (amorphous) stack

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ABSTRACT

We report the investigation of the in-plane azimuthal angular dependence of the magnetization reversal in the ion beam sputtered exchanged biased NiFe(111)/FeMn(111)/CoFeB(amorphous) stack. Compared to the as-deposited case, the magnetic annealing resulted in 3 fold enhancement in exchange bias but decrease in coercivity. The observed cosine dependence of exchange biased CoFeB layer on the in-plane azimuthal angle of applied field is corroborated with Meiklejohn and Bean model. The training effect associated with the exchange bias showed unconventional increase in coercivity after first cycle of hysteresis loop, while the exchange bias decreases sharply, and for subsequent cycles the exchange bias follows the empirical relation based on the energy dissipation in the AF layer. The ferromagnetic resonance (FMR) measurements also exhibited the in-plane azimuthal angle dependence of the magnetic resonance field indicating that the uniaxial and unidirectional anisotropies are *not* collinear, although they lie in the same plane. However, no misalignment between the unidirectional anisotropy and the exchange bias direction is observed. The misalignment angle between the uniaxial and unidirectional anisotropy, as measured by FMR, is found to be 10° and 14° for CoFeB and NiFe, respectively. This misalignment is attributed to the interface roughness as revealed by x-ray reflectance measurements.

1. Introduction

The horizontal shifting of the magnetic hysteresis (M–H) loop of ferromagnetic (FM) layer interfacially coupled to an antiferromagnetic (AF) layer, subsequent to cooling in the presence of magnetic field from above the Neel temperature of the AF layer, is known as exchange bias (EB) [1–5]. This exchange bias is a result of magnetic coupling at the interface of AF and FM layers, which induces a *unidirectional* magnetic anisotropy referred to as *exchange* anisotropy. The fundamental requirement of inducing the exchange bias is the higher magnetic anisotropy of the AF layer compared to the uniaxial anisotropy of the FM layer [3]. Although the complete theory for describing the exchange bias phenomenon is still lacking, several models/reports, however, suggest that the main origin of EB is the uncompensated interfacial spins associated with the AF layer which do not follow the magnetic field variation during the magnetization reversal and hence the shifting of the M–H loop occurs [2–4]. When the horizontal shifting of the MH loop is opposite to the FM's magnetization direction during the field cooling, EB is referred to *negative* EB, although the shifting of hysteresis loop in positive direction, i.e., along field cooling direction is also observed, known as *positive* EB, e.g., in FeF_2/Fe bilayers [6–9]. The EB has advanced applications in the spin valve magnetic tunnel junctions (MTJs) based on tunnel magnetoresistance (TMR) effect [10,11]. The CoFeB is a useful FM alloy for achieving large TMR values due its amorphous nature of growth at room temperature (RT) in MgO based MTJs [12,13]. However, amorphous nature of CoFeB makes difficult to achieve optimum EB required to pin one of the FM layers in the spin valve MTJs compared to the polycrystalline FM layers. Therefore, in CoFeB based MTJs, EB is achieved by using a synthetic AF layer having structure of AF/CoFe/Ru/CoFeB instead of direct contact of CoFeB with AF layer [14,15]. However, there are limited reports on the study of EB in IrMn/CoFeB bilayers [16,17]. It is recognized fact that EB depends critically on the interface roughness, diffusion across the interface, impurities, grain boundaries, etc. present in the AF and FM layers, which create magnetically frustrated regions of exchange coupled spins at AF–FM interfaces. All these factors affect the magnetization reversal process, the exchange anisotropy, the interlayer coupling, and sometimes lead to the asymmetry in the uniaxial and unidirectional anisotropies of the FM/AF system. It is well established that the angular dependence of

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magnetization reversal gives the qualitative understanding of exchange anisotropy, coercivity, interlayer coupling, and asymmetry in magnetization reversal [18–21]. The understanding of the magnetization reversal and asymmetry in uniaxial and unidirectional anisotropy is lacking in exchange bias systems, particularly, having amorphous FM layer. In this report, we present a detailed investigation of the angular dependence of the magnetization reversal in the FeMn(111)/CoFeB(amorphous) EB system using magneto optical Kerr effect (MOKE) measurements. The study revealed the misalignment between the uniaxial anisotropy of FM layer and unidirectional anisotropy of AF layer, and is well supported by the ferromagnetic resonance (FMR) measurements performed at different in-plane magnetic field orientations.

2. Experimental details

The multilayer stacks (as shown in Fig. 1) are deposited using ion beam sputtering on glass substrates at room temperature (RT). The Ta and NiFe layers are used for inducing the desired (111) orientation of *fcc* FeMn layer, conducive for exchange bias in CoFeB. For obtaining optimally moderate values of exchange bias field H_E (amount by which the center of the *M*–*H* loop shift along *H*-axis), we deposited three samples (G11, G12, and G13) by using different combinations of thickness of Ta and NiFe layers, as shown in Fig. 1. During the growth of the layer stacks, an in-plane magnetic field (H_{dep}) of 90 Oe was applied to induce uniaxial anisotropy in FM layers. After deposition, the layer stacks were annealed at 300 °C for 1 h in presence of 1.5 kOe magnetic field applied along the direction of H_{dep} during film growth (sample named as G13-300, and likewise for others). The *M*–*H* hysteresis loops were recorded at RT using longitudinal MOKE. The details of fabrication method and measurements are described in previous reports [22,23]. The x-ray diffraction patterns are recorded in θ–2θ configuration using Cu-K_α radiation. X-ray reflectance (XRR) is used to probe the interface properties of the layer stack. X-ray photoelectron spectroscopy (XPS) employing non-monochromatic MgK_α (1253.6 eV) was used to identify the composition and study the electronic structure of the FeMn film. To understand the magnetic anisotropy of FM and AF layer in G13-300, we recorded the angular dependence of the resonance field in a transmission line excited by electromagnetic radiation at a fixed frequency of 8.5 GHz using FMR technique. The angular dependence of FMR spectra is measured by keeping the sample on micro strip transmission line placed between the magnetic poles and rotating the electromagnet housed over a goniometer with a resolution of 1°.

3. Results and discussion

The *M*–*H* loops recorded at RT are shown in Fig. 2. The open triangles and solid circles represent *M*–*H* curves for as-deposited and magnetically annealed (300 °C/1 h) samples, respectively. It

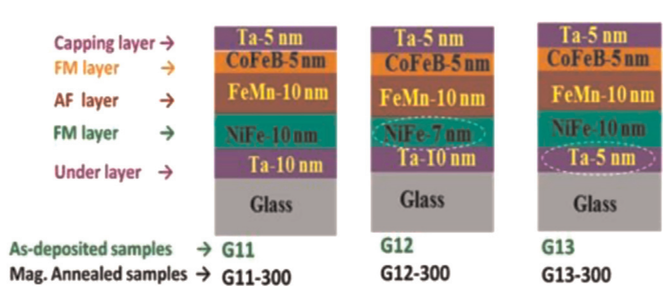

Fig. 1. The schematics of the deposited samples.

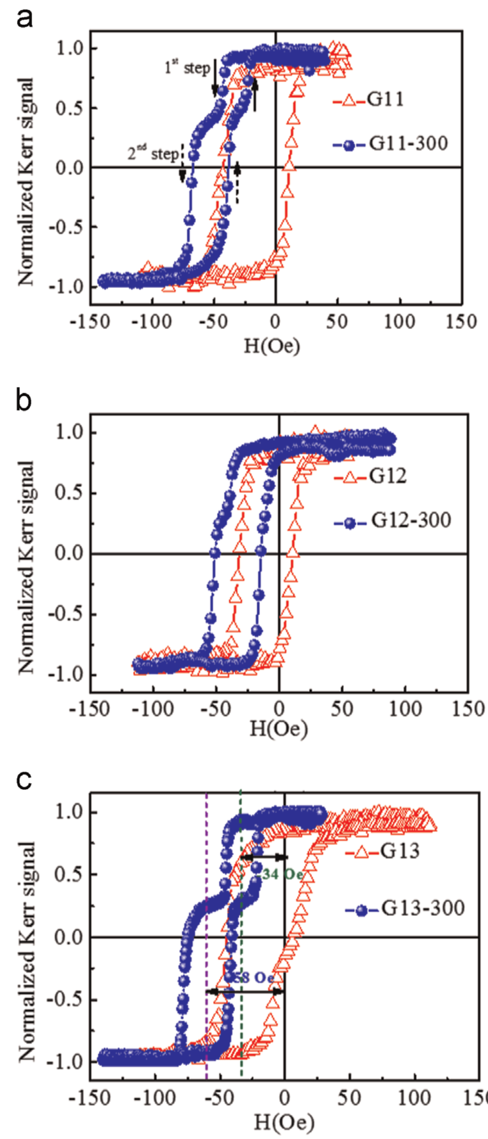

Fig. 2. MOKE *M*–*H* loops recorded for the as-deposited (open triangles) and magnetically annealed (solid circles) samples (a) G11 and G11-300 (b) G12 and G12-300 (c) G13 and G13-300.

can be seen that the hysteresis loop exhibits single magnetization reversal in as-deposited samples, while after magnetic annealing (G11-300), the magnetization reversal occurs in two steps, thereby forming a plateau region during overall magnetization reversal. These 1st and 2nd reversals correspond to the bottom FM layer of NiFe and upper CoFeB layer, respectively. The separate switching of these two FM layers is dependent on the thickness of the Ta buffer layer. Fig. 2(b) shows the hysteresis loop of G12-300 sample which exhibit very small field-separation between the two field reversal points indicating the presence of finite ferromagnetic coupling between NiFe and CoFeB layers across the AF FeMn layer, which may be associated to the interface roughness governed by the effect of lower NiFe thickness. When the thickness of NiFe is increased from 7 nm to 10 nm in sample G11-300, the plateau-width increased as shown in Fig. 2(a), which further become wider by decreasing Ta thickness from 10 to 5 nm in sample G13-300 (Fig. 2(c)), clearly indicating the separate switching of the two FM layers. Therefore, it is concluded that although the FeMn thickness is same in all the samples, but the magnetic coupling of the two FM layers across the AF FeMn is greatly affected by the combination of Ta and NiFe thicknesses. In all the three samples, in as-deposited