JOURNAL OF APPLIED PHYSICS **99**, 08C108 (2006)

Ferromagnetic resonance study of the exchange bias field in NiFe/FeMn/NiFe trilayers

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(Presented on 3 November 2005; published online 26 April 2006)

The ferromagnetic resonance (FMR) technique is used to study the exchange bias field in asymmetrical NiFe/FeMn/NiFe trilayers produced by dc magnetron sputtering under different working pressures. The FMR spectra give evidence of two resonance modes attributed to the two asymmetrical noninteracting NiFe layers. The study of the in-plane angular dependence of the absorption field allows the measurement of the exchange bias field at both bottom ferromagnetic (FM)/antiferromagnetic (AFM) and top AFM/FM interfaces. *© 2006 American Institute of Physics.*
[DOI: 10.1063/1.2176334]

Magnetic trilayers composed by two ferromagnetic films separated by a nonmagnetic spacer "represent the archetype of magnetic multilayers and nanostructures."[1] They offer several parameters that can be manipulated to control their magnetic properties, such as the dependence of the interlayer exchange coupling on the thickness of the nonmagnetic spacer. In ferromagnetic resonance (FMR) experiments, the interlayer coupling can give rise to acoustic and optic resonance modes. They arise from both magnetic layers and when the coupling is ferromagnetic (antiferromagnetic), the absorption field of the acoustic or uniform mode is higher (lower) than that of the optic mode.[2] Indeed, the difference between the absorption fields can be taken as a measure of the interlayer exchange coupling.[2,3] However, when the spacer layer is an antiferromagnetic material, instead of a nonmagnetic metal, an additional unidirectional anisotropy known as *exchange anisotropy* may arise from the interaction between the ferromagnetic (FM) and antiferromagnetic (AFM) layers. Indeed the exchange anisotropy has been observed in many systems containing FM/AFM interfaces, such as inhomogeneous materials and thin films.[4] The related exchange anisotropy field, also known as *exchange bias field* H_E, depends on the presence of uncompensated AFM spins at the FM/AFM interface generated by several factors, such as interfacial roughness, grain boundary disorder, and grain size distribution. The growing interest in exchange biased systems is due not only to the fact that a clear understanding of exchange anisotropy is still on the making,[5,6] but also to its use in magnetoelectronics devices.[7] Several different techniques have been used in the study of exchange anisotropy and related phenomena,[4] and FMR proved to be very useful.[4,8–10] In this work, the FMR technique is used to study the exchange bias field in NiFe/FeMn/NiFe trilayers.

Three $Ni_{81}Fe_{19}$(30 nm)/$Fe_{50}Mn_{50}$(15 nm)/$Ni_{81}Fe_{19}$(10 nm) trilayers, denoted as A2, A5, and A10, were deposited by dc magnetron sputtering at room temperature, under the Ar gas working pressures of 2, 5, and 10 mTorr, respectively. The base pressure before deposition was better than 5×10^{-8} Torr and the trilayers were all grown onto Si(100) substrates covered with a WTi (10 nm) buffer layer, and in the presence of an applied magnetic field of 460 Oe. They were also protected by another WTi (10 nm) cap layer to prevent oxidation. The real layers thicknesses obtained by fitting the respective x-ray reflectivity measurements,[11] ±0.5 nm for each layer thickness, are A2: Si(100)/WTi(6.7 nm)/NiFe(30.5 nm)/FeMn(13.6 nm)/NiFe(10.1 nm)/WTi(6.7 nm), A5: Si(100)/WTi(8.6 nm)/NiFe(32.6 nm)/FeMn(13.8 nm)/NiFe(10.3 nm)/WTi(9.4 nm), and A10: Si(100)/WTi(6.6 nm)/NiFe(30.2 nm)/FeMn(13.1 nm)/NiFe(10.1 nm)/WTi(7.1 nm).

The bottom FM/AFM and top AFM/FM interfaces roughnesses (±0.1 nm) are, respectively, 0.3 and 0.7 nm for trilayer A2, 0.8 and 1.1 nm for trilayer A5, and 1.0 and 2.7 nm for trilayer A10. These results show that the roughnesses of the interfaces increase with the working pressure in the deposition chamber and that the roughness of the bottom FM/AFM interface is always smaller than that of the top AFM/FM interface. The structural quality of the films was also assured by the x-ray diffraction patterns[11] with high peaks related to the (111)-NiFe and (111)-FeMn reflections and the narrow FMR lines. The FMR measurements were carried out at room temperature, using a commercial Bruker ESP-300 spectrometer operating at the microwave frequency of 9.79 GHz and swept static magnetic field. The FMR spectra were taken using standard modulation and phase sensitive detection techniques, with the film at the center of a high-Q cylindrical resonant cavity. Representative perpendicular and parallel FMR spectra as field derivatives of the absorbed power of trilayer A2 are shown in Figs. 1 and 3, respectively.

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0021-8979/2006/99(8)/08C108/3/$23.00

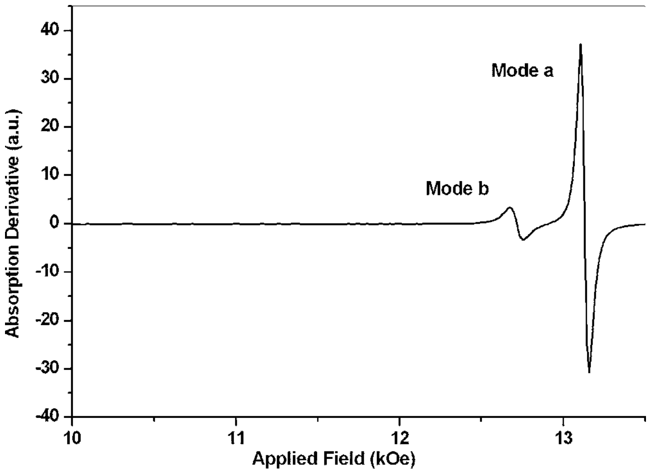

FIG. 1. Perpendicular FMR spectrum of trilayer A2. The absorption fields and linewidths values are, respectively, 13130 and 47 Oe for the main uniform mode a and 12 709 and 79 Oe for the second mode b.

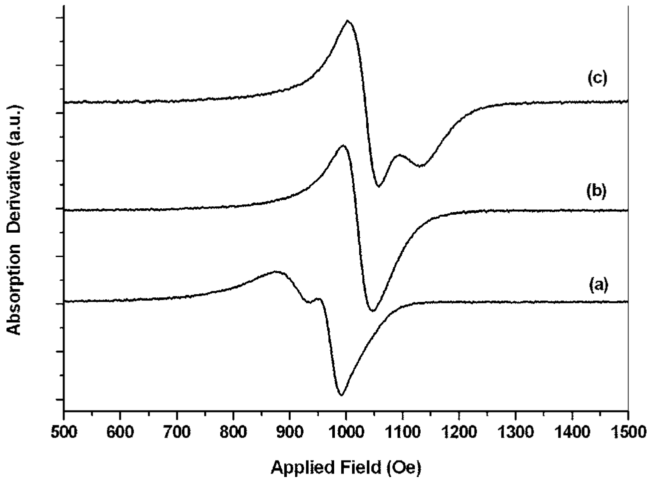

FIG. 3. Parallel FMR spectra of trilayer A2. In-plane applied static field (a) parallel, (b) perpendicular, and (c) antiparallel to the direction of the exchange bias field.

The perpendicular FMR spectrum of trilayer A2 (Fig. 1) shows the main uniform mode a with absorption field of 13 130 Oe and narrow linewidth of 47 Oe and a second and weak mode b with lower absorption field of 12 709 Oe and wider linewidth of 79 Oe. The perpendicular FMR spectra of trilayers A5 and A10 show similar resonance modes with absorption fields of 12 823 and 12 194 Oe and linewidths of 88 and 113 Oe, respectively for trilayer A5 and absorption fields of 12 041 and 10 466 Oe and linewidths of 71 and 300 Oe for trilayer A10. This behavior, however, does not give conclusive evidence that optic and acoustic (uniform) FMR modes were excited by the microwave field. The study of the angular dependence of the spectra and absorption fields of each film shows that as the applied field is turned away from the normal, a crossover point is observed at which the two modes have the same absorption field (Fig. 2). This is the behavior of nonexchange coupled asymmetrical trilayer structures in which the magnetic layers do not interact.[3] The mode with lower absorption field and wider linewidth must be attributed therefore to another magnetic phase in the film, with lower effective magnetization. We attribute the main mode a, to the bottom and thick NiFe layer and the mode b to the top and thin NiFe layer. The larger linewidth of mode b gives evidence of the effects of larger interface roughness and less homogeneous thin magnetic layer. Thus, the analysis of each independent mode can be carried on in terms of an energy density as the sum of contributions from Zeeman energy, magnetostatic energy, and first order anisotropy energy, using the well-known resonance conditions

$$\omega/\gamma = H_{\perp} - 4\pi M_{\mathrm{eff}} \quad \text{and} \quad (\omega/\gamma)^2 = H_{\parallel}(H_{\parallel} + 4\pi M_{\mathrm{eff}})$$

for perpendicular and parallel FMR, respectively. Here $4\pi M_{\mathrm{eff}}=4\pi M_s - H_k$ is the effective magnetization; $4\pi M_s$, the saturation magnetization; H_k, the perpendicular anisotropy field; ω, the microwave angular frequency; and $\gamma = ge/2m$, the gyromagnetic ratio. According to these resonance conditions, using the values of perpendicular and parallel FMR absorption fields, the effective magnetizations of the bottom and top NiFe layers are, respectively, 9737 and 9704 G for trilayer A2, 9603 and 9553 G for trilayer A5, and 8798 and 8673 G for trilayer A10. The well-known value of $4\pi M_s$ for NiFe is 9600 G.

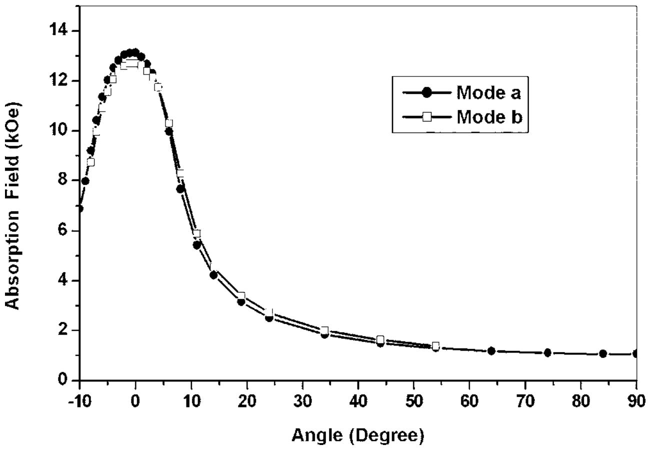

FIG. 2. Angular dependence of absorption fields of modes a and b of trilayer A2. The crossover point corresponds to the spectrum with the field direction at 4° from the normal to the film. The two modes are superposed, giving a single FMR line with absorption field of 11 747 Oe and a linewidth of 81 Oe. The same behavior is observed for trilayers A5 and A10 but with the field direction at 6° from the normal.

In parallel geometry of the applied field, in the absence of any in-plane magnetic anisotropy, when the external static field H_r is applied along the direction of the exchange bias field H_E, the effective field in each NiFe layer varies from $H_r(0)+H_E$, when H_r and H_E have the same direction, to $H_r(\pi)-H_E$, when they have opposite directions. The difference $[H_r(\pi)-H_r(0)]=2H_E$ gives therefore the FMR measure[8–10] of the exchange bias field. Parallel FMR spectra of trilayer A2 are shown in Fig. 3 for the static applied field parallel [Fig. 3(a)], perpendicular [Fig. 3(b)], and antiparallel [Fig. 3(c)] to the direction of the exchange bias field. They give evidence again of two resonance modes, with the same in-plane angular dependence, and show that the absorption field for the main mode a varies from 957 to 1034 Oe while that for the mode b varies from 913 to 1113 Oe. When the

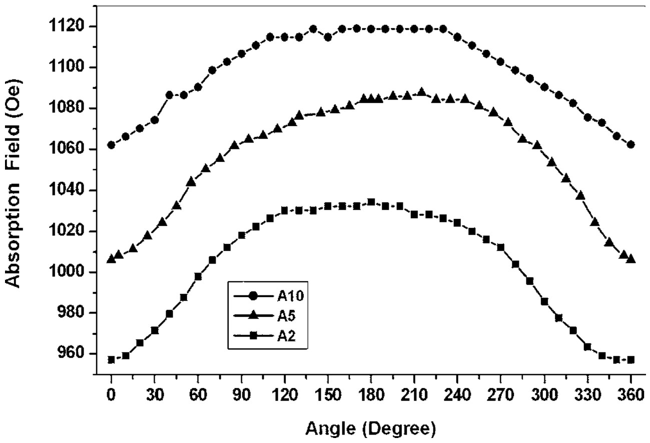

FIG. 4. Angular dependence of the in-plane absorption field of the uniform mode, deduced from the parallel FMR spectra of trilayers A2, A5, and A10. The exchange bias field is defined as $2H_E = H_r(\pi) - H_r(0)$.

static applied field is perpendicular to the direction of the exchange bias field, the two modes are superposed [Fig. 3(b)], the absorption field is 1018 Oe, and the linewidth is 53 Oe. The parallel FMR spectra and absorption fields of trilayers A5 and A10 also show similar in-plane angular dependence but do not show two well resolved resonance modes. The characteristic bell shape of the angular dependence of the absorption field of the main mode of each trilayer is shown in Fig. 4. The deduced values of the exchange bias field H_E (±4 Oe) are 39 Oe (bottom NiFe layer) and 100 Oe (top NiFe layer) for trilayer A2, 39 Oe (bottom NiFe layer) for trilayer A5, and 28 Oe (bottom NiFe layer) for trilayer A10. These results are comparable to the H_E values (±2 Oe) given by magnetization measurements:[11] 41 Oe (bottom NiFe layer) and 116 Oe (top NiFe layer) for trilayer A2, 26 Oe (bottom NiFe layer) for trilayer A5, and 29 Oe (bottom Ni Fe layer) for trilayer A10. The results for trilayer A2, for bottom and top NiFe layers, also give evidence that H_E is inversely proportional to the thickness of the FM layer.

In conclusion, the perpendicular FMR spectrum of each NiFe/FeMn/NiFe trilayer shows two resonance modes due to two noninteracting asymmetrical magnetic layers with distinct effective magnetizations and absorption fields. The parallel FMR spectra also give evidence of two resonance modes and respective absorption fileds with the same in-plane angular dependence, allowing at least for trilayer A2 the measurement of the exchange bias field at both bottom FM/AFM and top AFM/FM interfaces. The values obtained agree with magnetization measurements.

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