Measuring exchange anisotropy in Fe/MnPd using inductive magnetometry

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Local effective fields created in Fe by MnPd through exchange anisotropy are studied using an inductive ferromagnetic resonance technique. The bilayers were prepared on single crystal MgO(001) using ion beam sputtering in high vacuum and have a highly orientated crystalline structure with a [001] orientation as determined by x-ray diffraction. Unidirectional and fourfold anisotropies are measured using a stripline resonance geometry. Experiments with the field applied along different crystalline directions indicate that the fourfold axes are well defined with magnitudes consistent with values expected for bulk Fe. Anomalies in the frequency studied as a function of applied field are interpreted as evidence for a distribution of unidirectional anisotropy field orientations and strengths. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2713231]

Quasistatic hysterisis measurements of $M(H)$ require the interpretation of complicated magnetization processes involved in coercivity. This may lead to ambiguities in determing the exchange bias unidirectional anisotropy, particularly if the sample has different reversal mechanisms for different applied field directions. Ferromagnetic resonance measurement instead characterizes the curvature of the free energy, allowing a direct measurement of the exchange field. Local fields such as anisotropies and shape demagnetizing fields can be studied.[1–8] We use a stripline technique[9,10] to measure resonance in exchange biased Fe/MnPd.

In this report we show measurements of Fe films exchange coupled to MnPd films. Similar films grown by sputtering have been explored in some detail before,[11,12] largely from the point of view of reversal mechanisms. The Fe(220 Å)/MnPd(1000 Å) bilayer was grown on a single crystalline MgO substrate oriented along the [001] direction using ion beam sputtering[13] in an ultrahigh vacuum at less than 10^{-8} Torr. The ferromagnet was biased by sputtering the sample in a magnetic field of 300 Oe applied along the [100] easy axis of the Fe film. The structure of the film was investigated using x-ray diffraction measurements. Narrow widths in these results suggest that the Fe layer is highly orientated crystalline bcc and the MnPd layer is a highly orientated crystalline, chemically ordered, $L1_0$ structure with its c axis normal to the film plane. The epitaxial relationships are Fe[001]∥MnPd[001]∥MgO[001] (out-of-plane directions) and MnPd [110]∥Fe[100]∥MgO[110] (in-plane directions). Loops measured on a vibrating sample magnetometer (VSM) show a bias of 35 Oe. The high crystalline quality of the sample, supporting well defined high order anisotropies, motivates use of a simple model for the equilibrium magnetization as a function of applied field.

The magnetization is assumed to be uniform throughout the Fe film. The orientation of the applied field is in the film plane and specified by the angle θ, measured with respect to the [010] direction. The orientation of the magnetization is given at all locations in the film by the angles θ_{FM} and ϕ_{FM}, which are measured from the in plane direction [100] and the film normal [001], respectively. All crystal directions are given relative to the Fe crystal. The free energy F_T for the Fe film including unidirectional, shape demagnetizing, and fourfold anisotropies is given by

$$F_T = (K_\perp - 2\pi M_S^2)\sin^2(\phi_{\mathrm{FM}}) + \frac{K_\parallel}{4}[\sin^2(2\phi_{\mathrm{FM}}) + \sin^4(\phi_{\mathrm{FM}})\cos^2(2\phi_{\mathrm{FM}})] + K_U \sin^2(\phi_{\mathrm{FM}})\sin^2(\theta_{\mathrm{FM}}) - J_{\mathrm{int}} M_s \sin(\phi_{\mathrm{FM}})\cos(\theta_{\mathrm{FM}}) - HM_s \sin(\phi_{\mathrm{FM}})\cos(\beta - \theta_{\mathrm{FM}}). \quad (1)$$

The first term is the effective demagnetizing energy, where $2\pi M_s^2$ is the out-of-plane demagnetization and $K_\perp$ is a uniaxial anisotropy directed normal to the film plane. The second and third terms are the fourfold and uniaxial anisotropy energies, with anisotropy constants $K_\parallel$ and K_U, respectively. The symmetry axis of the uniaxial anisotropy is assumed to lie in plane along a [100] direction. The fourth term represents an exchange anisotropy due to exchange coupling at the interface between the ferromagnetic (FM) and the antiferromagnetic (AFM) films. The energy J_{int} corresponds to

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an effective volume unidirectional exchange anisotropy $J_{\text{int}} = H_E M_S$ aligned along a fourfold axis, where H_E is the interface exchange anisotropy field. Note that H_E should depend upon the Fe film thickness according to $1/t_{\text{Fe}}$, where t_{Fe} is the Fe film thickness. The last term is the Zeeman energy associated with the applied field H at an angle β.

Following the theory of Smit and Beljers,[14] ferromagnetic resonance occurs at a free energy given by

$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{M^2 \sin^2(\theta)}\left[\frac{\partial^2 \mathrm{F}}{\partial\theta^2}\frac{\partial^2 \mathrm{F}}{\partial\phi^2} - \left(\frac{\partial^2 F}{\partial\theta \cdot \partial\phi}\right)^2\right], \tag{2}$$

where the derivatives are taken with respect to the free energy of Eq. (1). Here ω is the microwave driving frequency and γ the gyromagnetic ratio. This expression is valid for spin wave excitations with very long wavelengths and for resonance in very thin films, and incorporates pinning effects as effective volume anisotropy terms. The frequency is a measure of the curvature of the energy at a local minimum. The significance of this is that contributions from the unidirectional anisotropy (and all other effective fields, for that matter) are evaluated with the magnetization near equilibrium. The frequency therefore contains information about local unidirectional exchange anisotropy which, as explained before, can be different magnetometry results.

The resonance frequency can be found from Eq. (1) for magnetization in plane as

$$\begin{aligned}\left(\frac{\omega}{\gamma}\right)^2 = {} & [H\cos(\beta-\theta_{\text{FM}}) + H_E\cos(\theta_{\text{FM}}) + H_A\cos(2\theta_{\text{FM}}) \\ & + H_{K1}\cos(4\theta_{\text{FM}})] \times \Bigg[H\cos(\beta-\theta_{\text{FM}}) - H_{u\,\text{eff}} \\ & + H_E\cos(\theta_{\text{FM}}) - H_A\sin^2(\theta_{\text{FM}}) + H_{K1}\Bigg(1 \\ & - \frac{1}{2}\sin^2(2\theta_{\text{FM}}\Bigg)\Bigg],\end{aligned} \tag{3}$$

where $H_E = J_{\text{int}}/M_s$, $H_{u\text{eff}} = 2(K_\perp - 2\pi M_s^2)/M_s$, $H_{K1} = 2K_\parallel/M_s$, and $H_A = 2K_u/M_s$.

Assuming that the effective demagnetization anisotropy forces the magnetization in plane, the magnetization angle θ_{FM} is determined by the condition

$$\begin{aligned}H\sin(\beta-\theta_{\text{FM}}) - H_E\sin(\theta_{\text{FM}}) - \frac{1}{2}H_A\sin(2\theta_{\text{FM}}) \\ - \frac{1}{4}H_{K1}\sin(4\theta_{\text{FM}}) = 0.\end{aligned} \tag{4}$$

Consider the case of the field applied along one of the fourfold anisotropy hard directions with $\beta = \pi/4$ if there is no uniaxial anisotropy. At zero field, the magnetization lies along an easy direction defined by the fourfold anisotropy. The magnetization will align with the applied field for sufficiently large applied field. The rotation into the field direction will be the same regardless of which easy direction the magnetization is along in zero field.

The situation is different if a unidirectional exchange anisotropy exists. Since H_E is defined to be along a fourfold anisotropy easy direction, there will be a discontinuous change possible in the magnetization angle θ_{FM} as the applied field is increased from zero. If the magnetization in zero applied field lies along the in plane axis which is *perpendicular* to the unidirectional axis, then there will be some critical applied field strength at which the magnetization will abruptly rotate to lie along a new direction.

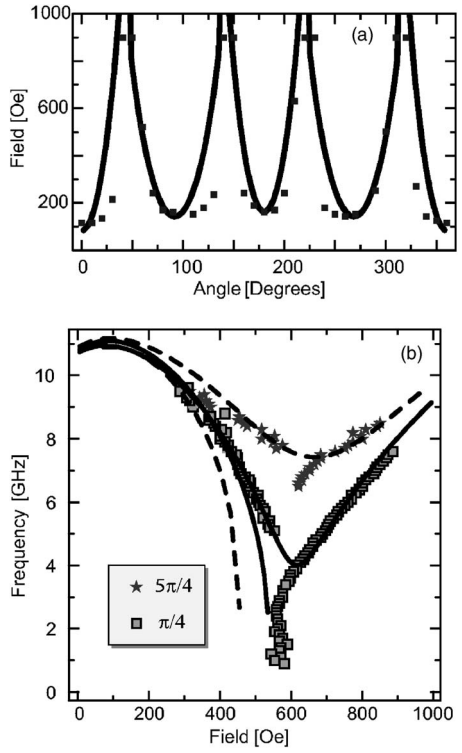

FIG. 1. (a) Resonant field as a function of angle at a constant frequency. Evidence for fourfold anisotsropy is clearly seen. The solid line is a theoretical fit derived from the free energy. (b) Ferromagnetic resonance (FMR) response as a function of field in the exchange bias sample with the applied field aligned along the hard axis at $\pi/4$ (results shown from field applied along both directions). A best fit overlayed from the model with parameters mentioned in the text.

Our inductive technique to measure the ferromagnetic resonance response of the MnPd/Fe sample consists of a microwave coplanar stripline on which the sample is placed. A network analyzer is used as both the excitation and measurement devices, coupling to the sample through mutual inductance with the waveguide. An Agilent (8719ET) network analyzer was used, which has a bandwidth of 13.5 GHz. The waveguide has a bandwidth of 40 GHz, and high frequency results were limited by the analyzer. The waveguide and sample are placed in an external applied field, with a maximum field strength of 900 Oe. A rotation stage allows orientates the sample to within 0.5° accuracy.

This broadband measurement system can determine resonance conditions at any field applied in plane. In these experiments the resonance is found as a maximum in the absorption measured from the signal transmitted through the waveguide. The field was swept at constant frequency. Frequencies were chosen in order to avoid any spurious standing waves in the coplanar waveguide. Experimental results for a 360° rotation of the sample at a fixed frequency are shown in Fig. 1(a). with the frequency fixed at 10.8 GHz. A fit to the data is shown using Eq. (3). As the fourfold anisotropy of the

Fe thin film layer has effective fields with roughly the same magnitude as the maximum applied field range available, it is difficult to obtain a complete resonant field profile as a function of angle for any one frequency. This is seen in Fig. 1(a) where orientations along hard directions do not have measurable data points at 10.8 GHz. However, the fourfold behavior is clearly visible, and the unidirectional exchange coupling can be seen as a difference in resonance between $\theta=\pi$ and 2π.

Measurements of resonance frequency were made with the field aligned along one of the fourfold hard axes and the frequency was recorded as a function of applied field strength. Examples are shown in Fig. 1(b), where results for the field applied along both directions of one hard axis are shown. Notice at our available applied field range that the measured frequencies along the hard direction are all below 10 GHz. The results are shown for the field along the $\pi/4$ direction by squares, and for the field along the $5\pi/4$ direction by stars. Comparison with Eq. (3) is shown in both cases. The solid lines represent the solutions for the $\pi/4$ direction while the dashed lines represent the solutions for the $5\pi/4$ direction.

Several general features appear in both alignments. The frequency lowers as the magnetization is pulled into the hard direction, reaching a minimum at the same field where the magnetization aligns with the applied field. Note that we have included two resonance branches in the results. One branch corresponds to the magnetization at zero field aligned along one easy axis, and the other branch corresponds to the zero field alignment along the other easy in plane axis. The unidirectional field is associated with a discontinuous change in the magnetization orientation. A softening of one branch of the resonance appears and indicates an orientational instability for the alignment of the magnetization preceding an abrupt reorientation transition. We do not find any experimental data points with frequencies that lie on this branch.

Increasing the applied field to a value greater than the effective field of the fourfold anisotropy causes the resonant frequency to increase, and accounts for the high field behavior above the frequency cusp where the magnetization is aligned with the applied field. The thin film approximation provides a good fit to the data in this high frequency region, and also for low frequencies. The best fit parameters for the experimental data above are $(h_E=-10\ \text{Oe}, h_{K1}=560\ \text{Oe})$. The same parameters are used for both orientations of the field.

Interestingly, there appears to be a jump in frequency for the transition to the hard direction for fields at the frequency cusp. This jump was confirmed not to display hysteretic behavior. It was identical whether the field was swept from positive to negative or vise versa. To explain the frequency behavior for these field values, and for field values near the frequency cusp, we propose that there may be a distribution of unidirectional H_E fields. Small variations in the unidirectional magnitude and orientation have effects similar to changing slightly the orientation angle of the applied field. Examples are shown in Fig. 2 where frequencies are calculated for small variations of the applied field angle from the $\pi/4$ and $5\pi/4$ values. A similar behavior is seen when we alter the strength of H_E. The result in either case is that a spread of frequencies appears and mimics what we might expect for resonance frequencies with a distribution of local exchange anisotropy fields.

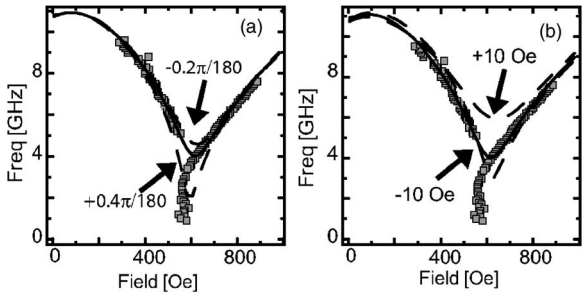

FIG. 2. Experimental data from applied field direction $\pi/4$ overlayed with fits from a distribution of (a) small deviations in bias angle from $\pi/4$. (b) Large deviations in bias strength from $h_E=+10$ to -10 Oe corresponding to complete reversal of bias direction for some regions of the interface. In both cases only the experimentally observed branch is shown, and the solid line shows best fit parameters.

A distribution of exchange anisotropy fields can thus account for the observed continuity of resonance frequencies as the magnetization orients into the applied field direction. As noted above, a discontinuity is expected in the frequency for fields where the magnetization rotates abruptly into the field direction. A distribution of exchange anisotropy fields would wash out this discontinuity and provide measurable resonances for all field values in the region of the reorientation.

We postulate the existence of pinning centers responsible for the exchange bias which themselves appear according to some distribution of strengths. We cannot say whether these pinning centers appear as pinned spins directly near the interface, or spins positioned further away from the interface. This means that we cannot make any statements as to the mechanism of exchange bias due to either domain state or pinned domain wall models. In either case, our measure of unidirectional exchange anisotropy fields provides information concerning the magnitude and distribution of exchange bias fields.

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[1] J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).
[2] H. Xi and R. M. White, Phys. Rev. B **61**, 80 (2000).
[3] R. D. McMichael, M. D. Stiles, P. J. Chen, and W. F. Egelhoff, Phys. Rev. B **58**, 8605 (1998).
[4] C. Mathieu, M. Bauer, B. Hillebrands, J. Fassbender, G. Guntherodt, R. Jungblut, J. Kohlhepp, and A. Reinders, J. Appl. Phys. **83**, 2863 (1998).
[5] P. Miltenyi, M. Gruyters, G. Guntherodt, J. Nogues, and I. K. Schuller, Phys. Rev. B **59**, 3333 (1999).
[6] H. Xi, R. M. White, and S. M. Rezende, J. Appl. Phys. **87**, 4960 (2000).
[7] L. Wee, R. L. Stamps, L. Malkinski, and Z. Celinski, Phys. Rev. B **69**, 134426 (2004).
[8] M. J. Pechan, D. Bennett, N. Teng, C. Leighton, J. Nogués, and I. K. Schuller, Phys. Rev. B **65**, 064410 (2002).
[9] T. J. Silva, C. S. Lee, T. M. Crawford, and C. T. Rogers, J. Appl. Phys. **85**, 7849 (1999).
[10] G. Counil, J.-V. Kim, T. Devolder, C. Chappert, K. Shigeto, and Y. Otani, J. Appl. Phys. **95**, 5646 (2004).
[11] P. Blomqvist, K. M. Krishnan, and E. Girt, J. Appl. Phys. **95**, 8487 (2004).
[12] P. Blomqvist, K. M. Krishnan, and D. E. McCready, J. Appl. Phys. **95**, 8019 (2004).

[13]N. Cheng, J. Ahn, and K. M. Krishnan, J. Appl. Phys. **89**, 6597 (2001).

[14]J. Smit and H. G. Beljers, Philips Res. Rep. **10**, 113 (1955).