Ferromagnetic resonance studies of surface and bulk spin-wave modes in a CoFe/PtMn/CoFe multilayer film

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We studied exchange-dominated surface and bulk spin-wave modes in a single period of CoFe/PtMn/CoFe trilayer film grown on a seed layer of Ru with CoFe film compositions being Co-16 at. %Fe. The thickness of the ferromagnetic CoFe layers is ~400 Å and that of the antiferromagnetic layer is 120 Å. Multimode spin-wave spectra were observed using the ferromagnetic resonance technique, as the sample plane was rotated with respect to the direction of the magnetic field. The effective magnetic anisotropy parameters and the g factor of the magnetic film were calculated from the field corresponding to the main (strongest) resonance peak at different angles. In addition, we identified a high-order standing spin wave in our spectra and found a "critical angle" in the multilayer sample. As H is significantly rotated away from the normal, there is a critical orientation where only a single acoustic spin-wave mode can be observed. We included an effective surface anisotropy field to describe our results. From the surface anisotropy, we are able to analyze the spin-wave resonance spectra in terms of the dynamic surface spin pinning. This allows us to determine the exchange interaction stiffness in the CoFe layers, $J \sim 2.7$ meV. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2839337]

Polycrystalline ferromagnetic/antiferromagnetic/ferromagnetic multilayer structures have been studied extensively for their potential applications in rf/microwave technology including magnetic band stop filters and magnetic integrated inductors.[1,2] These metallic multilayer films have a high saturation magnetization, and the physical vapor deposition process for the structures are low temperature processing technologies compatible with the silicon integrated circuits and monolithic microwave integrated circuits process.[3] These properties make them promising candidates for developing microwave devices. One such example is the Ru-seeded CoFe/PtMn/CoFe sandwich structure, which showed excellent magnetic softness with a low hard axis coercivity of 2–4 Oe and a significant enhancement of in-plane anisotropy: ~57–123 Oe.[3] It is well established that magnetic properties in the multilayer film are closely related to the magnetic surface and interface states;[4–6] however, our understanding of the fundamental dynamical magnetic excitations—which is intimately connected with the exchange interaction between different layers—is still far from complete. Magnetization dynamics in films can be carried out by various experimental techniques, such as the ultrafast magneto-optical Kerr effect,[7–9] Brillouin light scattering,[10] and ferromagnetic resonance (FMR).[11,12]

In this paper, we used the FMR technique to investigate exchange-dominated surface and bulk spin-wave modes in a single period of CoFe/PtMn/CoFe trilayer film. We calculated the bulk magnetic anisotropy parameters and the g factor of the magnetic film based on the angle dependence of the main (strongest) resonance field. Additionally, a high-order standing spin wave was identified in our spectra along with a "critical angle" in the trilayer sample. We included an effective surface anisotropy field due to the exchange bias and the dynamic surface spin pinning to describe our results. As a result, we were able to determine the exchange interaction stiffness in the CoFe layers, $J \sim 2.7$ meV.

The single-period CoFe/PtMn/CoFe trilayer film was grown on a seed layer of Ru with CoFe film compositions being Co-16 at. %Fe, the details of which are reported elsewhere.[3] The thickness of the ferromagnetic CoFe layers is ~400 Å and that of the antiferromagnetic layer is 120 Å. FMR measurements were carried out at X band (~9.74 GHz) using a Bruker EMX electron paramagnetic resonance spectrometer. The experimental setup and the polar coordinate system used in the subsequent discussion are plotted in the inset of Fig. 1. The dc magnetic field H was applied in the horizontal plane and the microwave magnetic field was along the vertical direction. The sample was placed in a quartz tube inserted in the microwave cavity and rotated with respect to H in an orientation between the normal to the layer plane ($\theta=90°$) and the in-plane orientation ($\theta=0°$).

Figure 1 illustrates spin-wave resonance (SWR) spectra for various magnetic field orientations of the trilayer CoFe film. For a configuration close to out of plane ($\theta \sim 90°$), in addition to a broadband feature on the high field side of the spectrum, which is attributed to an exchange-dominated non-propagating surface mode, two SWR lines can be well re-

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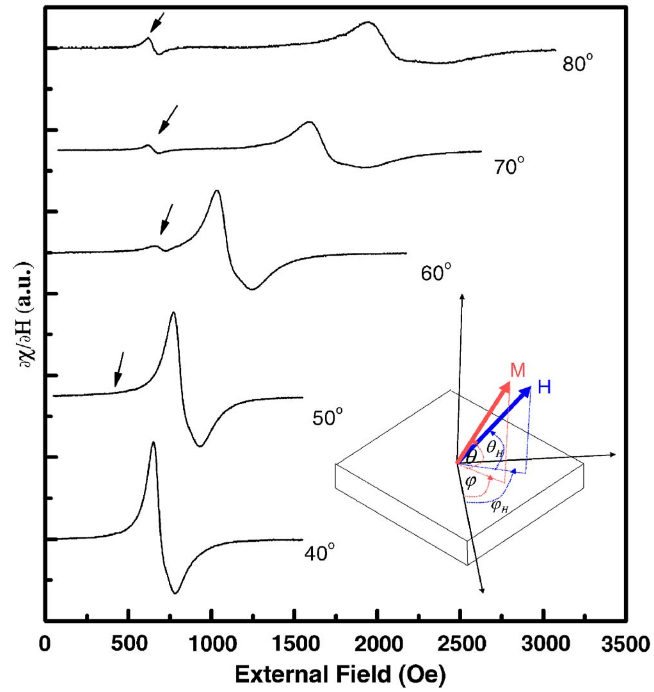

FIG. 1. (Color online) SWR spectra for the eight periods of CoFe/PtMn/CoFe trilayer film at various angles (θ) between H and in-plane orientation. The inset shows the coordinate system used to describe the sample configuration.

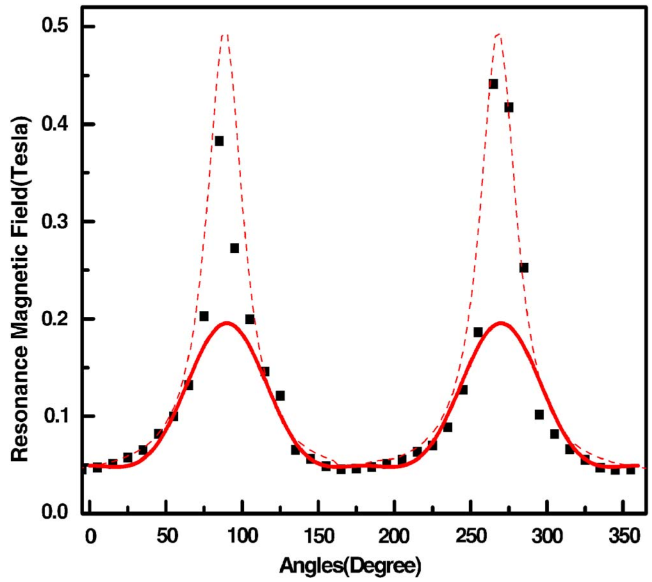

FIG. 2. (Color online) Resonant fields of the uniform spin-wave mode as a function of the dc magnetic field orientation with respect to the sample in-plane orientation. The dashed and solid lines show the fitting with and without including dynamical surface pinning condition.

solved. These lines are identified as the acoustic spin-wave (SW) mode and high-order standing SW modes. When we rotate **H** away from the perpendicular orientation, the high-order SWR mode (as indicated by the black arrows in Fig. 1) gradually loses its intensity. Eventually, at a critical angle θ_C ($\sim 50°$), the multi-SW spectrum vanishes except for the single narrow resonance line due to the uniform FMR mode. We note that the complex behavior of angular dependence of the SWR spectrum described above shows some similarities to those previously reported in Permalloy[13] and half-metallic ferromagnetic films.[14] The results could be related to the change of surface spin pinning as discussed below.

Figure 2 plots the angular dependences of the resonance field of the acoustic spin-wave mode. We observe a clear twofold symmetry for the out-of-plane geometry that is consistent with the magnetization measurements of the CoFe trilayer film. We use the Landau–Lifshitz equation of motion to describe our results:

$$\partial \mathbf{M}/\partial t = \gamma \mathbf{M} \times [\mathbf{H} - \nabla_{\mathbf{M}} F_A + D M^{-1} \nabla^2 \mathbf{M}], \qquad (1)$$

where $F = \Sigma_{i=1,2}\{-2\pi M_t^2 t_F \cos^2\theta_i - K_{Ui} t_F \sin^2\theta_i - K_{Ai} t_F \cos^2\theta_i \sin^2\phi_i - M_i H_{Ei} \sin\theta_i \cos\phi_i\} + J\hat{M}_i \cdot \hat{M}_2$ is the demagnetization field and the magnetic anisotropy contribution for the ferromagnetic layers to the free energy.[8,15,16] t_F is the thickness of the ferromagnetic layer, K_U and K_A are out-of-plane uniaxial and effective in-plane anisotropy constants, H_E is the exchange bias field between the CoFe layer and PtMn layer, and H is the external field strength. The excitation of the spin-wave procession is due to the absorption of microwave. For the case of saturated magnetic field ($H_{\mathrm{res}} \gg H_{\mathrm{coercivity}}$), we can get that the normal modes are the in-phase (acoustic mode) and out-of-phase (optical mode) precessions of $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$.[11] As compared to that of the acoustic mode, the optical mode has a higher resonant field, but much weaker intensity.[11] Here, we focus our discussion on the strongest spin-wave precession, the acoustic mode only. We have a solution to Eq. (1) for the in-phase spin-wave precession including both the bulk and the surface contributions. The eigenfrequencies of the acoustic mode are

$$\omega^2 = \gamma^2 \left[H_0 + \left(4\pi M - \frac{2K_U}{M} \right) \cos 2\theta \pm D\alpha^2 \right] \times \left[H_0 + \left(-4\pi M + \frac{2K_U}{M} \right) \sin^2\theta - \frac{2K_A}{M} \pm D\alpha^2 \right]. \qquad (2)$$

Here, we neglect the exchange bias field between the CoFe layer and the PtMn layer since $H_E \sim 0$ when the thickness of CoFe layer is ~ 400 Å. This is further confirmed by our magnetization measurements.[17] We select the actual acoustic eigenmodes by the boundary conditions which mainly depend on *dynamical surface spin pinning* condition.[18] We include an effective surface anisotropy field ($\boldsymbol{K}_{\mathrm{surf}}$), which was first introduced by Puszkarski[19] to explain our results. According to the theory of surface states in SWR, the change of spin energy at each film surface and interface can be described by an effective parameter:

$$A(\theta,\varphi) = 1 - \frac{g\mu_B}{2SzJ}(\boldsymbol{m} \cdot \boldsymbol{K}_{\mathrm{surf}}), \qquad (3)$$

where S is the atom spin, J is the Heisenberg exchange interaction parameter between two nearest spins, z is the number of nearest-neighbor spins in a crystal lattice, $\boldsymbol{K}_{\mathrm{surf}}$ is the effective surface anisotropy field, and $\boldsymbol{m}$ is the unit vector of magnetization. As shown in Fig. 3, the value of A gives us a measurement of the strength of the interlayer exchange coupling and spin pinning at the surface, and the angular depen-

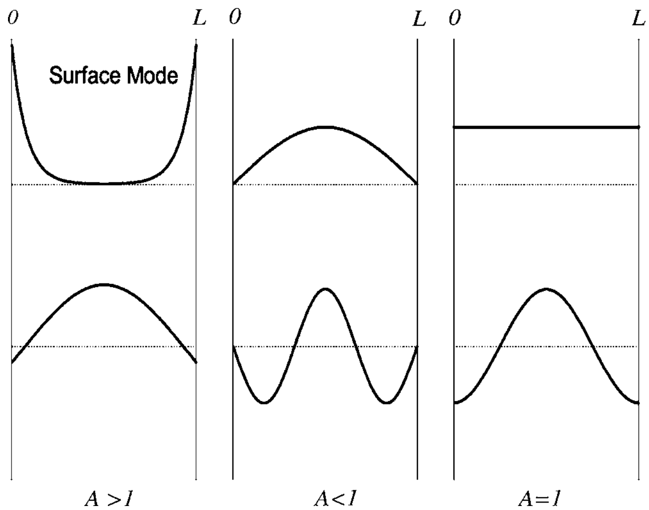

FIG. 3. Shape of the symmetric spin-wave mode (n=0 and 2) for three specific surface pinning conditions.

dent SWR spectra can be qualitatively explained by this equation. In detail, when $A<1$, surface spins are *pinned* and multibulk SWR modes with real values of the wave vectors k are expected.[13] For this case, the resonance field of SWR modes conforms to the Kittel model.[20] As H tilts away from the perpendicular direction of layer plane, A increases and so that the surface spin pinning fades away. When it reaches its critical-angle orientation, we have free boundary condition for surface spins: $A=1$ (i.e., $\theta_C \sim 50°$). Only one resonance peak, corresponding to the uniform mode where $k=0$, remains. The critical angle corresponds to the disappearance of surface anisotropy, which has also been defined as the "natural surface defect." If we further increase the tilting of H, the spins at surface are unpinned ($A>1$). The energy of all the spins present per unit area of the surface can be written as $E_S = 2S^2 zJd^{-2}(A-1)$, with d the lattice constant. Since $\boldsymbol{K}_{\text{surf}}$ is a constant vector and m rotates with external magnetic field, we have E_S changing with the orientation of $\boldsymbol{H}$.

The solid line in Fig. 2 shows the fitting of the present SWR data using Eq. (2). We obtained the following: $g = 2.01$, $2K_A/M \sim 0.1$ T, and $4\pi M - 2K_U/M \sim 1.9$ T. The values are greatly consistent with what we got from our magnetization measurements. However, it is evident that the experimental resonance data show a large deviation from the theoretical prediction (fitting), particularly when H is oriented close to the perpendicular direction of the film. The dashed line in Fig. 2 shows the new fit after compensating for the surface dynamical pinning. We calculated the exchange interaction constant in the CoFe layers as $J \sim 2.7$ meV (for a cubic ferromagnet, the exchange constant $J = D/2Sd^2$, with S the spin value of magnetic ion). The good fit of the experimental data by including the surface energy indicates that we need to consider the energy contribution from the surface spin excitations. This is extremely important for designing magnetoelectronic devices based on nanoscale structures. In addition, as we can see from Eq. (3), the effective parameter A varies with changing angles when we rotate the sample, and the magnetic profile changes due to the change of the surface pinning. This results in the change of the spin-wave resonance energy.

In summary, we studied fundamental magnetic excitations in a CoFe/PtMn/CoFe multilayer film using FMR technique. A high-order spin-wave mode was observed above a certain critical angle. By including an effective surface anisotropy field, we are able to explain the SWR spectra in terms of dynamic surface spin pinning.

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