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Isotropic ferromagnetic resonance field shift in as-prepared permalloy/FeMn bilayers

S.J. Yuan[1,3], Y.X. Sui[2], and S.M. Zhou[1,a]

[1] Surface Physics Laboratory (State Key Laboratory) and Department of Physics, Fudan University, Shanghai 200433, China
[2] Center for Material Analysis and Measurements, Nanjing University, Nanjing 210093, China
[3] Department of Physics, Shanghai University, Shanghai 200444, China

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Abstract. Exchange-coupled wedged-permalloy (Py)/FeMn bilayers are studied by ferromagnetic resonance (FMR) technique at room temperature. In comparison, Py single layer films were also made. For Py single layer films and Py/FeMn bilayers, only one uniform resonance peak was observed at high magnetic fields, indicating no interfacial diffusion at the Py/FeMn and Py/Cu interfaces. Negative isotropic in-plane resonance field does exist in Py/FeMn bilayers and its magnitude increases with decreasing Py layer thickness. In order to explain above phenomena, interfacial perpendicular anisotropy must be considered simultaneously, in addition to irreversible rotation of spins in FeMn layers. This is because the perpendicular resonance field of the bilayers is larger than that of Py single layer films.

PACS. 75.70.-i Magnetic properties of thin films, surfaces, and interfaces – 75.70.Cn Magnetic properties of interfaces (multilayers, superlattices, heterostructures) – 76.50.+g Ferromagnetic, antiferromagnetic, and ferrimagnetic resonances; spin-wave resonance – 75.30.Gw Magnetic anisotropy

1 Introduction

Ferromagnet/antiferromagnet (FM/AF) exchange biasing has attracted much attention because of its importance in both basic research and applications, such as giant magnetoresistance devices [1–3]. Several distinguished features have been found for the exchange-biased FM/AF bilayers, including the exchange field and the coercivity enhancement, rotational hysteresis loss, asymmetrical magnetization reversal process, and isotropic in-plane resonance field shift $H_{\rm ISO}$ [1,2,4,5]. First, after establishment of the exchange biasing, the hysteresis loop of the pinned FM layer will be shifted away from the zero magnetic field with the shift amount denoted as the exchange field $H_{\rm E}$ and the coercivity is usually enhanced, in comparison with corresponding free FM layer. The exchange field is inversely proportional to the FM layer thickness $t_{\rm FM}$ and the enhanced coercivity usually decreases with increasing $t_{\rm FM}$. In this case, the FM layer has a unidirectional anisotropy. Secondly, in magnetometer measurements, the magnetization reversal process is different for the ascent and descent branches, denoted as asymmetry of magnetization reversal. Thirdly, in torque measurements, the angular dependence of the torque displays an additional $\sin\phi_{\rm H}$ component, where $\phi_{\rm H}$ is the angle of the applied field and the unidirectional anisotropy axis. Finally, in ferromagnetic resonance (FMR) measurements, the in-plane resonance field $H_{\rm res}$ of the pinned FM layer is shifted towards to lower or higher magnetic fields, in comparison with corresponding free FM layer. The shift in the average value of the in-plane resonance field $H_{\rm ISO}$ is not equal to zero.

Although $H_{\rm ISO}$ has been observed in several groups, it has not been understood very well [6,7,10–12]. Earlier theoretical work attributed $H_{\rm ISO}$ to a surface perpendicular anisotropy because it is inversely proportional to $t_{\rm FM}$ [6,7]. Actually, a positive or negative interfacial perpendicular anisotropy was found in permalloy (Py)/CoO multilayers and Co/FeMn bilayers [8,9]. Therefore, the effective demagnetization field $4\pi M_{\rm eff}$ in FM/AF bilayers might be different from that of single layer films. For example, if the interfacial perpendicular anisotropy is negative, the in-plane resonance field $H_{\rm res}$ of bilayers is smaller than that of single layer films and the perpendicular $H_{\rm res}$ should be larger than that of single layer films. One can find that $H_{\rm ISO}$ is negative. For Py/NiO bilayers, however, $H_{\rm res}$ was found to be smaller than that of Py single layer films in *all orientations* from $\theta_{\rm H} = 0$ to 90 degrees, where $\theta_{\rm H}$ is the angle between the normal direction and the external field. $H_{\rm ISO}$ was interpreted as a result of irreversible transitions of AF spins by Stiles et al. [10] Another theoretical work argued that the irreversible rotation of the AF spins produce nonuniform $H_{\rm ISO}$ [11]. A positive $H_{\rm ISO}$ has recently been observed in Py/FeMn

[a] e-mail: shimingzhou@yahoo.com

bilayers and argued to arise from either specific geometry of Py layer thickness or an interfacial diffusion [12].

As discussed above, the interfacial perpendicular anisotropy at FM/AF might be of great influence on the in-plane H_{res}. Moreover, the g-factor should be taken into account because it also has an effect on the in-plane H_{res}. In order to clearly investigate the mechanism of H_{ISO}, H_{res} of FM single layer films and FM/AF bilayers should be measured at all orientations and the effects of $4\pi M_{eff}$ and the g-factor must be considered. In this paper, we prepared wedged-Py/FeMn bilayers and studied the relaxation characteristics for as-prepared samples. In comparison, Py single layer films with wedge shape were also prepared and studied. No field cooling procedure was made for Py/FeMn bilayers to avoid any interfacial diffusion.

2 Experiments

Two large samples (5 cm × 0.5 cm) of substrate/Cu/Py/FeMn/Cu and substrate/Cu/Py/Cu were fabricated on Si(100) substrates by DC magnetron sputtering system using targets of Cu, $Ni_{81}Fe_{19}$, and $Fe_{50}Mn_{50}$. The base pressure is typically 10^{-8} torr and Ar pressure 5 mtorr during deposition. The deposition rates of constituent layers were about 0.2 nm/s. A magnetic field of 130 Oe was applied perpendicular to the wedge direction and parallel to the film plane during deposition. To facilitate the observation of FM layer thickness effect, a wedge-shaped Py layer with t_{FM} from 0 to 25 nm was used, whereas the FeMn and Cu layers have a uniform thickness of 15 nm and 30 nm, respectively. Each large sample was cut into small pieces (0.3 cm × 0.2 cm) along the wedge direction, thus providing many small samples prepared at the same time but varying in t_{FM}.

Before measurements, no field-cooling procedure was performed for all the bilayers. FMR measurements were carried out at room temperature, using a Bruker ER 200D-SRC EPR spectrometer, with a fixed microwave frequency of 9.78 GHz and swept external static magnetic field. The samples were mounted on the side of a quartz rod and a goniometer was used to vary the angle. All measurements were made at room temperature.

3 Results and discussion

Figure 1a shows typical in-plane FMR spectra, i.e., field derivative of absorbed power for Py/FeMn bilayers. First, one can find that the resonance field H_{res} changes with the azimuthal angle of the applied magnetic field ϕ_H. Secondly, there is no interfacial diffusion in the present Py/FeMn bilayers and Py single layer films because only one intense uniform resonance peak is observed at high magnetic fields for all bilayers and single layer films. It is noted that no post-annealing treatment was made for Py/FeMn bilayers. The shape of the resonance peak has an asymmetry in all orientations, which was argued to

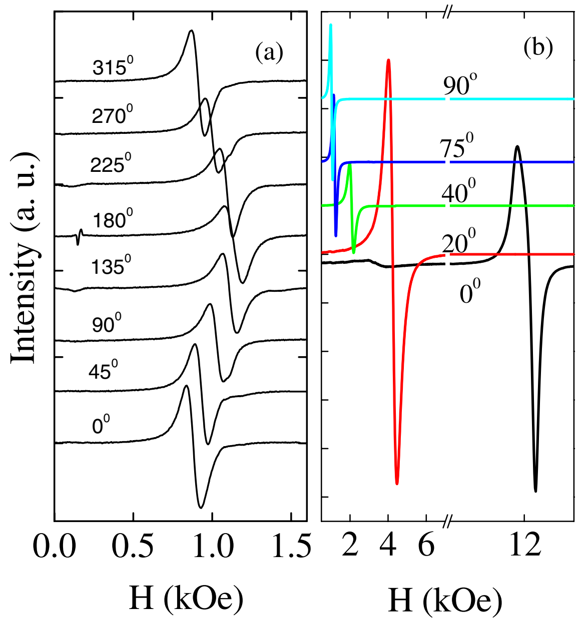

Fig. 1. In-plane (a) and out-of-plane (b) FMR spectra of Py/FeMn bilayers with $t_{FM} = 6.5$ nm. The inset numbers refer to the orientations of the external magnetic field ϕ_H in (a) and θ_H in (b).

be caused by the magnetic inhomogeneity in the Py layers [13,14]. The resonance line shape can be approximately described by the Lorentzian function and therefore H_{res} can be fitted. Additionally, a small step is observed in the low magnetic field region for FM/AF bilayers, around $\phi_H = 180$ degrees. Similar phenomena were observed in other FM/AF systems, in which the field of the step was found to be close to the sum of the exchange field and the coercivity, i.e., the switching field of the FM magnetization [12,15]. Figure 1b shows the typical out-of-plane FMR spectra for Py/FeMn bilayers with 6.5 nm. The out-of-plane resonance field shifts towards low magnetic fields with increasing θ_H.

Figure 2a shows typical angular dependence of the in-plane H_{res} for Py single layer films and Py/FeMn bilayers. For single layer films, in-plane H_{res} have the same values at $\phi = 0$, 180, and 360 degrees and thus the angular dependence can be fitted by considering uniaxial anisotropy. For Py/FeMn bilayers, H_{res} at $\phi = 180$ degrees is larger than that of $\phi = 0$ and 360 degrees, indicating the existence of the exchange biasing, and thus the angular dependence can be fitted by considering the unidirectional and uniaxial anisotropies. The exchange field, approximately taken as the difference of the in-plane resonance field between $\phi_H = 0°$ and $\phi_H = 180°$, increases with decreasing t_{FM}. Figure 2b shows the typical experimental and simulated results about the angular dependence of the out-of-plane H_{res} for the Py single layer and the Py/FeMn bilayer with 6.5 nm thick FM layer, where $\phi_H = 90°$ in order to suppress the effect of the exchange biasing on the out-of-plane angular dependence of the resonance field [5]. The

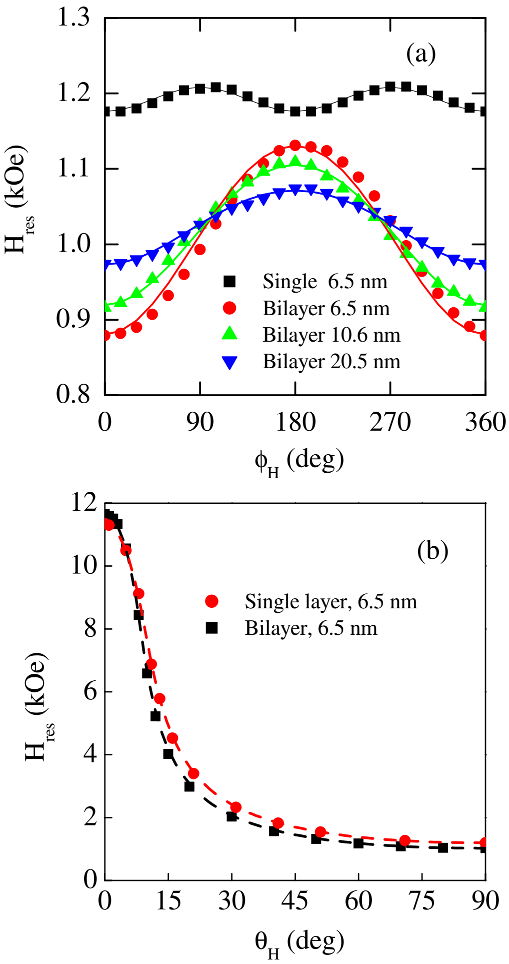

Fig. 2. Angular dependence of the in-plane (a) and out-of-plane (b) H_{res} for Py single layer films and Py/FeMn bilayers. All the solid and dashed lines are fitted results. The inset mubers refer to the FM layer thickness.

resonance field decreases with increasing θ_{H}, demonstrating the signature of the magnetic hard axis in the film plane.

Figure 2a also shows that at the same t_{FM} the in-plane H_{res} of Py/FeMn bilayers is smaller than that of Py single layer films at all orientations ϕ_{H}. Therefore, the average value of the in-plane resonance field of bilayers is smaller than that of Py single layer films. Without comparison in the perpendicular H_{res} between bilayers and single layer films, however, it is difficult to correctly analyze the mechanism of the resonance field shift because the in-plane resonance field shift in the FM/AF bilayers can be induced by two major reasons. First, an additional interfacial anisotropy can be induced at FM/AF bilayers and has an influence on the effective demagnetization field $4\pi M_{\mathrm{eff}}$. The g factor of the FM layer might also be influenced by the neighboring AF layer. In this way, the in-plane resonance field might be altered by the neighboring AF layer. This can be seen from the results in Figure 2b. At $\theta_{\mathrm{H}} = 0°$, the out-of-plane resonance field of the bilayer

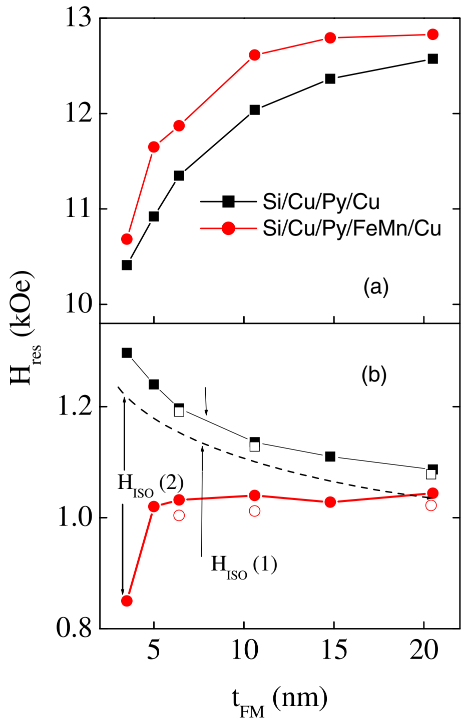

Fig. 3. Dependence of the perpendicular H_{res} at $\theta_{\mathrm{H}} = 0$ (a) and in-plane H_{res} (b) on t_{FM} for Py single layer films (square) and Py/FeMn bilayers (circle). In (b) solid squares and solid circles refer to the in-plane H_{res} at $\theta_{\mathrm{H}} = 90°$ and open squares and open circles to the average values of the in-plane one. The dashed line matches the perpendicular H_{res} of bilayers without irreversible rotation of AF spins.

is larger than that of the single layer film with the same FM layer thickness, and vice versa for $\theta_{\mathrm{H}} = 90°$. Secondly, an isotropic in-plane resonance field shift can be induced by the irreversible rotation of AF spins [5,6]. In order to see the second effect on the resonance field shift, it is essential to measure the angular dependence of the out-of-plane H_{res}.

Figure 3 shows the perpendicular H_{res} and the parallel one for Py single layer films and Py/FeMn bilayers as a function of t_{FM}. For specific Py layer thickness, the perpendicular H_{res} and the parallel one of Py/FeMn bilayers are larger and smaller than corresponding values of single layer films, respectively. This phenomenon can be attributed to a negative interfacial perpendicular anisotropy at Py/FeMn bilayers [6]. For Py single layer films and Py/FeMn bilayers, the perpendicular H_{res} increases sharply with initially increasing t_{FM} and approaches a constant with further increasing. However, the in-plane H_{res} has different variation trends for single layer films and bilayers. For Py single layer films, the in-plane H_{res} increases with decreasing t_{FM}, matching the variation of the perpendicular H_{res} while for Py/FeMn bilayers the in-plane H_{res} *decreases* sharply with decreasing t_{FM}. Only with the additional interfacial perpendicular anisotropy at Py/FeMn, the in-plane H_{res} of bilayers should vary with a trend marked by the dashed curves in Figure 3b, which matches with the out-of-plane $H_{\rm res}$. The difference between the value provided by the dashed line and that of the single layer films, denoted as $H_{\rm ISO}(1)$, is induced by the difference of the effective demagnetizing field and the g factor. Unambiguously, the difference between the experimental value of the in-plane $H_{\rm res}$ of Py/FeMn bilayers and that of the dashed curve, denoted as $H_{\rm ISO}(2)$, decreases with increasing FM layer thickness. In order to account for $H_{\rm ISO}(2)$, the irreversible rotation of AF spins must be considered [5,10]. The variation of $H_{\rm ISO}(2)$ indicates the interfacial nature of the exchange basing. Therefore, the isotropic resonance field shift $H_{\rm ISO}$ consists of $H_{\rm ISO}(1) + H_{\rm ISO}(2)$.

Let the FM/AF bilayer lie in the $x-y$ plane, with the z axis normal to the film plane. The uniaxial and unidirectional axes are aligned along the x direction. The orientations of the magnetization $\overrightarrow{M}_{\rm FM}$ and the external magnetic field $\overrightarrow{H}$ are defined by the angles θ and ϕ, $\theta_{\rm H}$ and $\phi_{\rm H}$ in spherical coordinates, where $\phi/\phi_{\rm H}$ is the angles between the magnetization or the external field and the axis x. $\theta/\theta_{\rm H}$ is the angles between the magnetization or the external field and the axis z. The total free energy per unit area can be written as follows [11].

$$\begin{aligned} E_{\rm T} = & (2\pi M_{\rm FM}^2 t_{\rm FM} - K_{\rm S})\cos^2\theta - K_{\rm U} t_{\rm FM}\sin^2\theta\cos^2\phi \\ & - H_{\rm E} M_{\rm FM} t_{\rm FM}\cos\phi - H M_{\rm FM} t_{\rm FM} \\ & \times(\sin\theta_{\rm H}\sin\theta\cos(\phi-\phi_{\rm H}) + \cos\theta_{\rm H}\cos\theta) \end{aligned} \quad (1)$$

where the first and the second terms represent the sum of the shape anisotropy and the interfacial perpendicular anisotropy, and the in-plane uniaxial anisotropy energies, respectively. The third term is the FM/AF exchange coupling energy. The last term refers to the Zeeman energy. $K_{\rm S}$ and $K_{\rm U}$ are interfacial and in-plane uniaxial anisotropies, respectively. One can have the following dispersion relationship for the in-plane configuration.

$$\begin{aligned} \left(\frac{\omega}{\gamma}\right)^2 = & \Big[H_{\rm res}\cos(\phi_{\rm H}-\phi) + H_{\rm ISO}(2) \\ & + H_{\rm E}^{\rm FMR}\cos\phi + H_{\rm K}\cos 2\phi\Big] \\ & \times\Big[4\pi M_{\rm eff} + H_{\rm ISO}(2) + H_{\rm res}\cos(\phi_{\rm H}-\phi) \\ & + H_{\rm E}^{\rm FMR}\cos\phi + H_{\rm K}\cos^2\phi\Big] \end{aligned} \quad (2)$$

where ω is the resonance frequency and γ is the magnetogyric ratio, the in-plane uniaxial anisotropy field $H_{\rm K} = \frac{2K_{\rm U}}{M_{\rm FM}}$, the effective demagnetization field $4\pi M_{\rm eff} = 4\pi M_{\rm FM} - 2K_{\rm S}/t_{\rm FM}M_{\rm FM}$. $H_{\rm ISO}(2)$ comes from the irreversible rotation of the AF spins. As shown below, for Py/FeMn bilayers, $4\pi M_{\rm eff} \sim 8$ kOe, the in-plane $H_{\rm res} \sim 1.0$ kOe, and $H_{\rm K}$ and $H_{\rm E}^{\rm FMR} \sim 0.1$ kOe. Therefore, $4\pi M_{\rm eff} \gg H_{\rm res} \gg H_{\rm K}, H_{\rm E}^{\rm FMR}$, equation (2) can be further simplified [15].

$$H_{\rm res} = \frac{\omega^2}{4\pi M_{\rm eff}\gamma^2} - H_{\rm ISO}(2) - H_{\rm E}^{\rm FMR}\cos\phi_{\rm H} - H_{\rm K}\cos 2\phi_{\rm H} \quad (3)$$

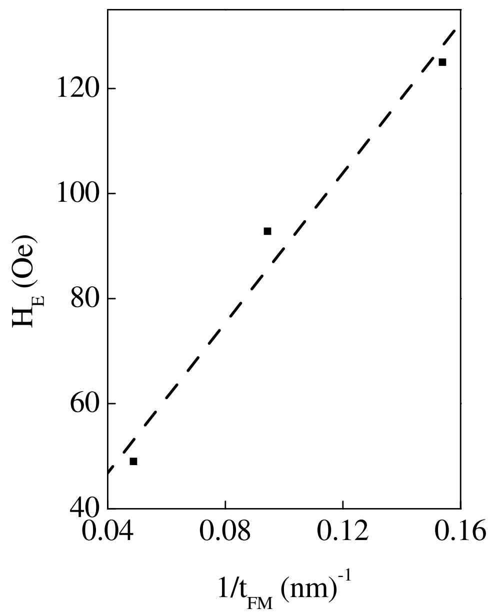

Fig. 4. For Py/FMn bilayers, dependence of the exchange field on the FM layer thickness can be fitted as a linear function of $1/t_{\rm FM}$. The dashed line refers to the fitted results.

where $\frac{\omega^2}{4\pi M_{\rm eff}\gamma^2}$ and $H_{\rm ISO}(2)$ are independent of the angle $\phi_{\rm H}$. The former one can be obtained by fitting the angular dependence of the out-of-plane $H_{\rm res}$. $H_{\rm ISO}(1)$ is the difference of $\frac{\omega^2}{4\pi M_{\rm eff}\gamma^2}$ between bilayers and single layer films. As shown in Figure 2a, the experimental angular dependence of the in-plane $H_{\rm res}$ can be fitted by using equation (3), and the $H_{\rm E}^{\rm FMR}$, $H_{\rm K}$, and $\frac{\omega^2}{4\pi M_{\rm eff}\gamma^2} - H_{\rm ISO}(2)$ can be determined. The resonance field shift is isotropic with respect to the orientation $\phi_{\rm H}$. This is controversial to the theoretical prediction by Xi et al., in which the resonance field shift was argued to be non-uniform [11]. Therefore, Xi's model cannot be used to explain the results of present Py/FeMn bilayers.

With equation (1), one can also obtain the dispersion relationship of the out-of-plane $H_{\rm res}$, which can be expressed below.

$$\begin{aligned} \left(\frac{\omega}{\gamma}\right)^2 = & [H_{\rm res}\cos(\theta_{\rm H}-\theta) - 4\pi M_{\rm eff}\cos\ 2\theta] \\ & \times\left[H_{\rm res}\cos(\theta_{\rm H}-\theta) - 4\pi M_{\rm eff}\cos^2\theta\right]. \end{aligned} \quad (4)$$

In this equation, the so-called rotational hysteresis loss and any effect related to the irreversible rotation of AF spins are not considered. As shown in Figure 2b, the simulated and measured results are in good agreement with each other. The g-factor and $4\pi M_{\rm eff}$ of single layer and bilayers can be obtained. For 6.5 nm thick Py single layer film and Py (6.5 nm)/FeMn bilayers, $g = 2.1$ and 2.24, $4\pi M_{\rm eff} = 8024$ Oe and 8527 Oe, respectively. Figure 4 shows the fitted values of the exchange field $H_{\rm E}$ from the angular dependence of the in-plane resonance field in Figure 2a. One can find that the exchange field

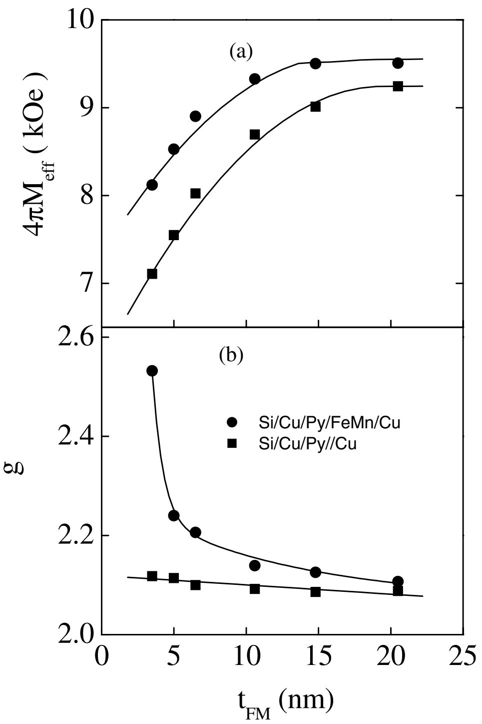

Fig. 5. Dependence of the $4\pi M_{\rm eff}$ and g factor on $t_{\rm FM}$ for Py single layer films and Py/FeMn bilayers. The solid lines serve as a guide to the eye.

decreases with increasing FM layer thickness and scales as a linear function of the $1/t_{\rm FM}$, displaying an interfacial nature of the exchange biasing.

Figure 5a shows the $t_{\rm FM}$ dependence of $4\pi M_{\rm eff}$ for Py single layer films and Py/FeMn bilayers. For Py single layer films, $4\pi M_{\rm eff}$ decreases with decreasing $t_{\rm FM}$, which can be explained as follows. First, the magnetization of the FM layers decreases with decreasing $t_{\rm FM}$, due to finite size effect. For small $t_{\rm FM}$, the Curie temperature of the FM layers might become lower, resulting in a reduction of the room temperature magnetization. Secondly, the interfacial perpendicular anisotropy at Py/Cu and Cu/Py might also have an influence on $4\pi M_{\rm eff}$. If the interfacial perpendicular anisotropic energy is positive and magnetization is independent of $t_{\rm FM}$, $4\pi M_{\rm eff}$ will also decrease with decreasing $t_{\rm FM}$. Figure 5a also shows that $4\pi M_{\rm eff}$ of bilayers is larger than that of single layer films, leading to a positive $H_{\rm ISO}(1)$. It can be attributed to a negative interfacial perpendicular anisotropy in Py/FeMn bilayers. For positive interfacial perpendicular anisotropy, however, the in-plane $H_{\rm res}$ of bilayers will be larger than that of single layer films, resulting in a positive $H_{\rm ISO}(1)$. The positive $H_{\rm ISO}$ was observed in field-cooled Py/FeMn bilayers [12], in which a positive interfacial perpendicular anisotropy might be introduced during field cooling procedure.

Figure 5b shows the $t_{\rm FM}$ dependence of the g-factor for Py single layer films and Py/FeMn bilayers. For thick Py single layer films, the g-factor is close to 2.0, indicating that the unquenched orbital angular momentum of Py films is negligible. The g-factor changes slightly with $t_{\rm FM}$. This is because the atomic environment of Fe and Ni atoms at Py/Cu interface is different from the inner one. For Py/FeMn bilayers, the g-factor is much larger than that of single layer films, especially for small $t_{\rm FM}$. The unquenched orbital angular momentum and thus corresponding magnetic contribution of bilayers are much larger than those of Py single layer films. The present simulation was argued to be misleading because the g factor is too large [5]. Another kind of simulations about the angular dependence of the out-of-plane $H_{\rm res}$ for Py/NiO bilayers was carried out, in which the g-factor and $4\pi M_{\rm eff}$ were assumed to be the same as those of single layer films. Up to now, no ideal theoretical work has been proposed to calculate the angular dependence of the out-of-plane $H_{\rm res}$ in FM/AF bilayers. New theoretical model must be proposed, in which the interfacial perpendicular anisotropy at FM/AF bilayers and the contribution from the irreversible rotation of AF spins must be considered simultaneously [5,10].

4 Conclusions

Py/FeMn bilayers and Py single layer films were prepared by DC magnetron sputtering and are studied by FMR technique at room temperature. For Py single layer films and Py/FeMn bilayers, only one uniform resonance peak was observed at high magnetic fields. Thus no interfacial diffusion exists at the Py/FeMn and Py/Cu interface. For Py/FeMn bilayers, the in-plane resonance field is smaller than that of the single layer films with the same FM layer thickness. More remarkably, the difference is increased with decreasing FM layer thickness. Apparently, isotropic in-plane resonance field shift does exist. In order to explain above phenomena, both interfacial perpendicular anisotropy and irreversible rotation of AF spins must be considered. This is because the perpendicular $H_{\rm res}$ of bilayers is larger than that of corresponding single layer films.

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