Magnetic coupling in asymmetric FeCoV/Ru/FeNi trilayers

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(Presented 6 November 2013; received 23 September 2013; accepted 7 November 2013; published online 10 February 2014)

We have investigated the magnetic anisotropy and interlayer coupling in trilayer films of permendur(100 Å)/Ru/permalloy(100 Å), with the thickness of the Ru spacer varying from 0 to 200 Å. While the permendur/permalloy sample exhibits a small in-plane uniaxial magnetic anisotropy with $H_u = 27$ Oe, all trilayers are magnetically isotropic in-plane. Results from hysteresis loop and ferromagnetic resonance measurements were fitted to a micromagnetic model, with the results indicating that all the films are ferromagnetically coupled except the one with 10 Å Ru spacer, which shows antiferromagnetic coupling. The trilayers with Ru spacer layer thickness larger than 20 Å exhibit only very weak ferromagnetic coupling. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4864743>]

I. INTRODUCTION

A trilayer system with two ferromagnetic (FM) layers separated by a non-magnetic (NM) spacer layer is of great interest due to its use in applications such as magnetic recording devices and non-volatile magnetic random memories.^{1,2} The interlayer coupling between the two FM layers plays an important role for engineering the magnetic properties of the trilayer systems and there have been numerous studies on coupled trilayers. However, most of the investigations have been carried on symmetrical trilayers with the two FM layers made from the same material. Reports on the exchange coupling in trilayers with different FM layers such as Fe/Cu/Ni³ and Ni/Cu/Co⁴ are more scarce. In this paper, we present our investigation of the interlayer coupling in trilayer films of permendur(Pmd)/Ru/permalloy(Py). The Pmd/Ru/Py system enables us to perform layer resolved spin dynamic studies using time-resolved X-ray Magnetic Circular Dichroism (XMCD) measurements, which will be reported later.

II. EXPERIMENTAL

The films were deposited at room temperature using dc magnetron sputtering. The base pressure of deposition was 5×10^{-8} Torr. The thin films consist of Si/Pmd(100 Å)/Ru(t_{Ru} Å)/Py(100 Å), with a 10 Å Ru layer added as cap. The chemical composition of the Pmd and Py alloys is Fe₄₉Co₄₉V₂ and Fe₁₉Ni₈₁, respectively. The Ru layer thickness was varied between 0 and 200 Å. The Ru spacer layer was deposited at low sputtering rate (0.4 Å/s) and low Ar gas pressure (3 mTorr) for optimal uniformity and interface smoothness.

Room temperature magnetization versus field curves were measured using a SQUID magnetometer. We also performed XMCD studies at the Fe, Ni, and Co $L_{2,3}$ edges. This element specific technique allows us to determine the magnetic state of the separate magnetic layers as each of them contains two different magnetic elements; Ni in the Py layer and Co in the Pmd layer. The samples were also studied in a field-sweep cavity ferromagnetic resonance (FMR) system with an RF frequency of 9.8 GHz. Angle dependent FMR measurements were performed using a goniometer, keeping the DC magnetic field parallel to the film plane. FMR spectra using a vector network analyzer based FMR system (VNA-FMR) were additionally recorded. Frequency scans at different magnetic fields ranging from 0.2 to 1.2 kOe were performed.

III. MICROMAGNETIC MODEL

We consider a trilayer system with two FM layers of the same thickness t , which are spaced by a NM Ru layer with thickness t_{Ru} . The coordinate system and geometry deployed in the study are shown in the left top inset of Fig. 1. The external magnetic field H is applied along the x -axis. Due to the demagnetizing field, which is much larger than any possible perpendicular anisotropy field, the magnetization in the two FM layers will be confined to the film plane. Taking into account the Zeeman energy, exchange energy, and demagnetizing energy, the total energy per unit area of the system is

$$\begin{aligned} \epsilon_{\text{tot}} &= \epsilon_{\text{zee}} + \epsilon_{\text{ex}} + \epsilon_{\text{dem}} \\ &= -tH(M_A \cos \phi_A + M_B \cos \phi_B) - J_1 \cos(\phi_A - \phi_B) \\ &\quad - J_2 \cos^2(\phi_A - \phi_B) - 2\pi t(M_A^2 \cos^2 \theta_A + M_B^2 \cos^2 \theta_B), \quad (1) \end{aligned}$$

where J_1 and J_2 are the bilinear and biquadratic coupling constants. When J_1 dominates over J_2 , a positive (negative) J_1 corresponds to ferromagnetic (antiferromagnetic) coupling.

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FIG. 1. Some typical magnetization curves of the Pmd/Ru/Py trilayers. The top left inset shows the geometry and coordinate system of the film samples. The right bottom inset shows ϕ_A and ϕ_B as a function of external field for the $t_{\text{Ru}} = 10 \text{ Å}$ sample.

For a given set of parameters describing the trilayer system (J_1 , J_2 , M_A , and M_B), the equilibrium orientation of the magnetizations (ϕ_A , ϕ_B) at any external field can be calculated numerically by finding the values of ϕ_A and ϕ_B minimizing ϵ_{tot} . Using these values, the static magnetization of the film is given by

$$m = \frac{M(H)}{M_s} = \frac{M_A \cos \phi_A + M_B \cos \phi_B}{M_A + M_B}. \quad (2)$$

In the FMR experiments, a microwave signal generating an RF magnetic field $\vec{h}$ that is perpendicular to the static field is used. Resonance absorption occurs when the microwave frequency matches the natural frequency of the system, which is determined by the magnetic properties of the sample and the static magnetic field. By substituting the energy density expression ϵ_{tot} and the equilibrium angles into the Suhl Smit equation⁵ and following a similar analysis as in Ref. 6, the resonance condition is obtained as a fourth order polynomial equation of the microwave angular frequency ω , which reads

$$a\omega^4 + c\omega^2 + e = 0. \quad (3)$$

The coefficients of the 4th order polynomial equation are

$$\begin{aligned} a &= \left(\frac{t^2 M_A M_B}{\gamma_A \gamma_B} \right)^2, \\ c &= -t^2 M_A M_B \left[\left(\frac{h_1^A h_2^A}{\gamma_B^2} + \frac{h_1^B h_2^B}{\gamma_A^2} \right) + \frac{2C_0 C_2}{\gamma_A \gamma_B} \right. \\ &\quad + C_1 \left(\frac{t M_A h_2^B}{\gamma_A^2} + \frac{t M_B h_2^A}{\gamma_B^2} \right) + C_2 \left(\frac{t M_A h_1^B}{\gamma_A^2} + \frac{t M_B h_1^A}{\gamma_B^2} \right) \\ &\quad \left. + C_1 C_2 \left(\frac{M_A}{M_B \gamma_A^2} + \frac{M_B}{M_A \gamma_B^2} \right) \right], \\ e &= [t^2 M_A M_B + C_2 (t M_A h_2^A + t M_B h_2^B)] \\ &\quad \times [t^2 M_A M_B h_1^A h_1^B + C_1 (t M_A h_1^A + t M_B h_1^B) + (C_1^2 - C_0^2)], \quad (4) \end{aligned}$$

with γ_A and γ_B being the gyromagnetic ratio of the FM layer A and B, respectively. The parameters in Eq. (4) are defined as $C_0 = J_1 + 2J_2 \cos(\phi_A - \phi_B)$, $C_1 = J_1 \cos(\phi_A - \phi_B) + 2J_2 \cos^2(\phi_A - \phi_B)$, $C_2 = J_1 \cos(\phi_A - \phi_B) + 2J_2 \cos 2(\phi_A - \phi_B)$, $h_1^{A(B)} = H \cos \phi_{A(B)} + 4\pi M_{A(B)}$, and $h_2^{A(B)} = H \cos \phi_{A(B)}$.

Among the four solutions of Eq. (3), only two are physically meaningful. These two resonances are referred to as the acoustic mode, which corresponds to the two magnetization vectors in the two FM layers resonating in-phase and the optic mode, which corresponds to the two magnetizations in the two FM layers resonating out-of-phase.

IV. RESULTS AND DISCUSSION

The results from angle dependent field-sweep cavity-FMR measurements show that all trilayer samples are isotropic in-plane. The Pmd/Py bilayer sample exhibits a small in-plane uniaxial anisotropy characterized by an anisotropy field of $H_u = 27 \text{ Oe}$. The in-plane magnetization curves for some of the films are presented in Fig. 1. The hysteresis loops of the films indicate that all films are ferromagnetically coupled except the one with 10 Å Ru spacer, which shows antiferromagnetic coupling instead. In addition, the XMCD studies performed in remanence were found to agree with the hysteresis measurements. Analyzing the difference spectra between the left and right circularly polarized light collected at the Ni and Co L edges (not shown), we find that Ni and Co moments are aligned antiparallel to each other for the sample with 10 Å thick Ru spacer, while for the other samples they are aligned in parallel. The antiferromagnetically coupled sample is characterized by a bilinear coupling constant of -0.57 erg/cm^2 and a small biquadratic coupling constant of -0.05 erg/cm^2 . The coupling constants were obtained by matching the calculated magnetization curve, using Eqs. (1) and (2), with the experimental data; the right bottom inset in Fig. 1 shows ϕ_A and ϕ_B as a function of external field for this sample. The saturation magnetization values used in the calculations are $4\pi M_A = 22 \text{ kG}$ for Pmd⁷ and $4\pi M_B = 9.5 \text{ kG}$ for Py.⁸

Figure 2 shows the dispersion relations (resonance frequency versus magnetic field) for some of the trilayer samples. The coupling constants were obtained by fitting the experimental cavity-FMR and VNA-FMR results to Eq. (3); the bilinear coupling constants are presented in Fig. 3. The simulated resonance frequency versus magnetic field curves fit the experimental data quite well, without introduction of the biquadratic coupling constant for any of the ferromagnetically coupled samples. However, for the antiferromagnetically coupled sample, a small biquadratic coupling constant of -0.05 erg/cm^2 was necessary to fit the experimental data. It is important to note that this value is much smaller compared to the bilinear coupling constant, implying that the coupling is dominated by the bilinear contribution. Interestingly, the best fit obtained from the FMR data yields $J_1 = -0.62 \text{ erg/cm}^2$, slightly different from the one obtained from the magnetization curves. This can be explained by the fact that in the micromagnetic model, discussed in Sec. III, we treated each layer of the film as a single magnetic domain

FIG. 2. The dispersion relations of Pmd/Ru/Py trilayers with $t_{\text{Ru}} = 0$ Å (green), $t_{\text{Ru}} = 10$ Å (red), $t_{\text{Ru}} = 15$ Å (blue), and $t_{\text{Ru}} = 20$ Å (magenta). Open and solid markers are experimental data obtained from VNA-FMR and cavity-FMR, respectively. Lines correspond to simulated curves using the micromagnetic model discussed in Sec. III, with solid lines representing the acoustic modes and dotted lines the optic modes. The inset shows the cavity FMR spectrum of the sample with $t_{\text{Ru}} = 15$ Å.

FIG. 3. Bilinear coupling constants as a function of t_{Ru} . The solid line is a guide to the eye.

and neglected effects of a multidomain state. Another comment we would like to add is that the VNA-FMR setup was unable to resolve the optic mode resonance peaks due to limitations in instrument sensitivity and the low intensity of the optic mode resonance.^{9,10}

As one can see from Fig. 3, the FM coupling for the Pmd/Py sample is comparably strong with $J_1 = 2 \text{ erg/cm}^2$. The coupling constant changes sign for the sample with 10 Å Ru thickness but changes back to FM coupling for larger Ru thickness. For Ru spacer thickness larger than 20 Å, the static Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling strength vanishes. Despite this, the films with Ru spacer thickness in the range of 20 Å–50 Å are still coupled as the FMR spectra

do not reveal two distinct resonance peaks for the Pmd and Py layers. This is tentatively explained by so-called dynamic exchange coupling interaction.¹¹ Further studies are under way. The coupling constants of our asymmetric trilayers exhibit values similar to that of symmetric Py/Ru/Py trilayers but its dependence on the Ru thickness is shifted toward the thicker end.^{12,13}

V. CONCLUSION

In conclusion, we have investigated the magnetic anisotropy and interlayer coupling in Pmd/Ru/Py trilayers grown on silicon substrates. The film without Ru spacer shows a weak in-plane uniaxial anisotropy with an anisotropy field of 27 Oe, while all of the trilayer samples were magnetically isotropic in-plane. The films are all ferromagnetically coupled except the one with 10 Å Ru spacer, which shows a relatively strong antiferromagnetic coupling characterized by a bilinear coupling constant $J_1 = -0.6 \text{ erg/cm}^2$ and biquadratic coupling constant $J_2 = -0.05 \text{ erg/cm}^2$. The bilayer Pmd/Py sample is strongly ferromagnetically coupled with a coupling constant of about 2 erg/cm^2 . The static RKKY coupling strength vanishes for Ru spacer thickness larger than 20 Å.

ACKNOWLEDGMENTS

This work was supported by the Swedish Research Council, the Knut and Alice Wallenberg Foundation, and the Swedish Foundation for Strategic Research.

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