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Interlayer Coupling of CoFe/Cu/NiFe Trilayer Films

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The interlayer coupling between adjacent ferromagnetic layers was examined for CoFe/Cu/NiFe trilayer systems. A series of films of CoFe (20 nm)/Cu(t_{Cu})/NiFe (20 nm) trilayers with Cu spacer thickness, t_{Cu}, in the range of 1~10 nm was deposited on Si(100) wafers at room temperature by DC magnetron sputtering. In order to understand the dependence of the magnetic interaction between ferromagnetic $Co_{90}Fe_{10}$ (wt.%) and $Ni_{81}Fe_{19}$ (wt.%) layers separated by a nonmagnetic Cu spacer on the Cu layer thickness, we investigated the derivative ferromagnetic resonance (FMR) spectra. The FMR results were analyzed using the model of Layadi and Artman for interlayer interaction. The interlayer coupling constant decreases in an oscillatory manner as the Cu spacer thickness increases up to 10 nm and approaches zero above 10 nm. The interlayer coupling constant is positive for all samples. Hence, it seems that the exchange coupling between adjacent CoFe and NiFe layers separated by a Cu layer is ferromagnetic.

1. Introduction

The interlayer coupling between adjacent ferromagnetic layers separated by nonmagnetic layers has been investigated for many years [1-4]. Layadi and Artman presented the theory of ferromagnetic resonance (FMR) responses of an interfacially coupled two-layer magnetic system [5]. They deduced the number, the position, the intensity, and the linewidth of the FMR peaks as functions of the coupling strength. Also, many workers have reported experimental evidence that magnetic interactions occur between ferromagnetic layers separated by a nonmagnetic interlayer. These studies have been performed by using FMR [6, 7], Brillouin light scattering (BLS) [8, 9], the surface magneto-optic Kerr effect (SMOKE) [10], and magnetoresistance (MR) [11]. Especially, FMR measurements are very useful to investigate the interlayer coupling because FMR absorption lines are sensitive to the magnetic interaction in multilayers [12].

In this work, FMR experiments were used to examine the interlayer coupling between adjacent ferromagnetic CoFe and NiFe layers for CoFe/Cu/NiFe trilayer films. By using the model of Layadi and Artman [5, 12] for interlayer interaction and FMR results, the coupling constant K was determined as a function of Cu spacer thickness.

2. Experimental

The CoFe (20 nm)/Cu(t_{Cu})/NiFe (20 nm) trilayer films used in this study were deposited on Si(100) wafers at room temperature using DC magnetron sputtering. The deposition rates were 0.18 nm/s for CoFe and Cu, and 0.20 nm/s for NiFe, respectively. The CoFe and NiFe sputtering target were alloy types. The background pressure was 7×10^{-7} torr, and the working gas pressure was 10 mTorr. Argon of 99.999% purity was used as the sputtering gas. The Cu spacer thickness t_{Cu} was varied from 1 nm to 10 nm.

The compositions of the $Co_{90}Fe_{10}$ (wt.%) and $Ni_{81}Fe_{19}$ (wt.%) films were checked using EDX (energy dispersive X-ray spectroscopy). The saturation magnetizations of the 20-nm-thick CoFe and the 20-nm-thick NiFe single layer were measured using a vibrating sample magnetometer (VSM). To investigate the interlayer exchange coupling between adjacent ferromagnetic CoFe and NiFe layers separated by the Cu layer, we performed ferromagnetic resonance measurements as follows: A disk-shaped sample with diameter $\Phi = 3$ mm was attached to the end of a quartz tube and placed in a cavity (TE_{011} mode) where the microwave and the DC magnetic field crossed each other. Under those conditions, derivative resonance signals were observed in the magnetic-field range 0~2000 Oe. The microwave frequency and power were 9.44 GHz and 0.1 mW, respectively. Using this method, we carried out the FMR measurements while the direction of the DC magnetic field was kept parallel to the film plane.

3. Results and Discussion

The saturation magnetization M_s of the CoFe and the

NiFe single layers were measured using a vibrating sample magnetometer. The values of $4\pi M_s$ of the 20-nm-thick $Co_{90}Fe_{10}$ (wt.%) and the 20-nm-thick $Ni_{81}Fe_{19}$ (wt.%) single layer were 19,350 G and 10,800 G, respectively.

The spectroscopic splitting factors g of the single layers were calculated from the following FMR conditions for the parallel and the perpendicular configurations [13-15]:

$$\left(\frac{\omega}{\gamma}\right)^2 = H_{\parallel}\ (\ H_{\parallel}\ + 4\pi M_s), \tag{1}$$

$$\frac{\omega}{\gamma} = H_{\perp} - 4\pi M_s, \tag{2}$$

where ω is the angular frequency of the microwave, γ ($=ge/2mc$) is the gyromagnetic ratio, and $H_{\parallel}$ and $H_{\perp}$ are the resonance fields for the parallel and the perpendicular configurations, respectively. The g values of the CoFe and the NiFe single layers were 2.08 and 2.14, respectively.

The experimental results of the CoFe/Cu/NiFe trilayer films are analyzed on the basis of a FMR-model for a coupled-ferromagnetic layers proposed by Layadi and Artman [4, 12]. Considering an interfacially coupled two-layer magnetic system which has a ferromagnetic (layer-A)/nonmagnetic/ferromagnetic (layer-B) structure, we can write the Landau-Lifshitz equations of motion with damping for the magnetization in this coupled system as follows:

$$t_A\frac{d\mathbf{M}_A}{dt}=\gamma_A t_A \mathbf{M}_A\times\mathbf{H}_A+\gamma_A\mathbf{M}_A\times K\mathbf{M}_B - \frac{\alpha_A t_A}{M_A}\mathbf{M}_A\times\frac{d\mathbf{M}_A}{dt}, \tag{3}$$

$$t_B\frac{d\mathbf{M}_B}{dt}=\gamma_B t_B \mathbf{M}_B\times\mathbf{H}_B+\gamma_B\mathbf{M}_B\times K\mathbf{M}_B - \frac{\alpha_B t_B}{M_B}\mathbf{M}_B\times\frac{d\mathbf{M}_B}{dt}, \tag{4}$$

where t_i ($i = A, B$) is the thickness of A or B layer, M_i is the magnetization, γ_i is the gyromagnetic ratio, α_i is the damping parameter, and K is the interlayer coupling constant. Eqs. (3) and (4) are then reduced to a set of four coupled equations that can be written in a four-by-four matrix form. When we set the real part of the determinant to zero, we end up with the following relation:

$$\begin{aligned} &K^2[-(\Omega_A M_A + \Omega_B M_B)^2 \\ &+(t_A H_{rA} M_A + t_B H_{rB} M_B)(M_A X + M_B Y)] \\ &+K[M_A(t_B H_{rB} + Y)(t_A H_{rA} X - \Omega_A^2) \\ &+M_B(t_A H_{rA} + X)(t_B H_{rB} Y - \Omega_B^2)] \\ &+(t_A H_{rA} X - \Omega_A^2)(t_A H_{rA} X - \Omega_A^2)=0 \end{aligned} \tag{5}$$

where

$$\Omega_A=\frac{t_A\omega}{\gamma_A}, \tag{6}$$

$$\Omega_B=\frac{t_B\omega}{\gamma_B}, \tag{7}$$

$$\omega=2\pi f, \tag{8}$$

$$X=t_A(H_{rA} - H_{kA}), \tag{9}$$

$$Y=t_B(H_{rB} - H_{kB}). \tag{10}$$

Where H_{ri} (i = A, B) and H_{ki}' are the resonance field for the parallel configuration and the effective magnetic anisotropy field, respectively, and f denotes the microwave frequency. By using Eq. (5), the experimental data for the γ_i's (i = A, B) and M_{si}, we can acquire the interlayer coupling constant K. If K is positive, the coupling is ferromagnetic; if K is negative, the coupling is antiferromagnetic.

Figure 1 represents the FMR spectra of CoFe (20 nm)/Cu(t_{Cu})/NiFe (20 nm) trilayer films when the DC magnetic field was applied parallel to the sample plane. In the case of the Cu spacer thickness t_{Cu}=1 nm, only one signal appears. In the range above 3 nm, two signals were observed. Considering the values of the saturation magnetization and the spectroscopic splitting factor of the $Co_{90}Fe_{10}$ film and the $Ni_{81}Fe_{19}$ films, we can see that the lower resonance field H_{rA} corresponds to the resonance of the CoFe layer and the higher H_{rB} corresponds to that of the NiFe layer.

Figure 2 shows the resonance fields H_{rA} and H_{rB} as a function of the Cu spacer thickness. The resonance fields show oscillatory variation with Cu spacer thickness.

By substituting the values of the γ_i's (i = A, B) and M_{si}'s of the CoFe and NiFe single layers into Eq. (5), we can obtain a pair of H_r vs. K curves. The results are shown in Fig. 3.

The K values of each sample can be obtained by plotting the measured values of H_{rA} and H_{rB} on Fig. 3 so as to fit each of them to the H_r vs. K curves. Figure 4 represents the interlayer coupling constant as a function of Cu spacer

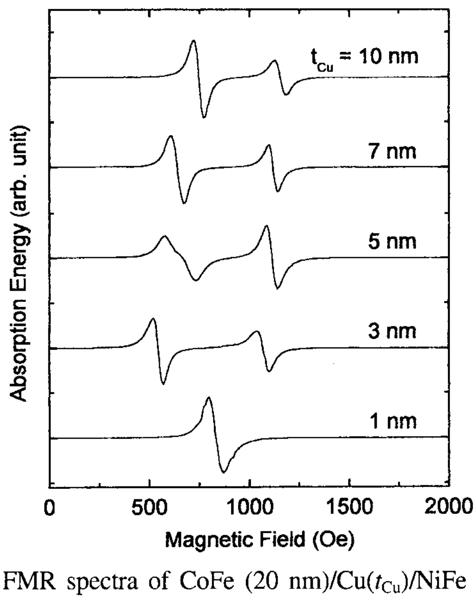

Fig. 1. FMR spectra of CoFe (20 nm)/Cu(t_{Cu})/NiFe (20 nm) trilayer films in parallel configuration.

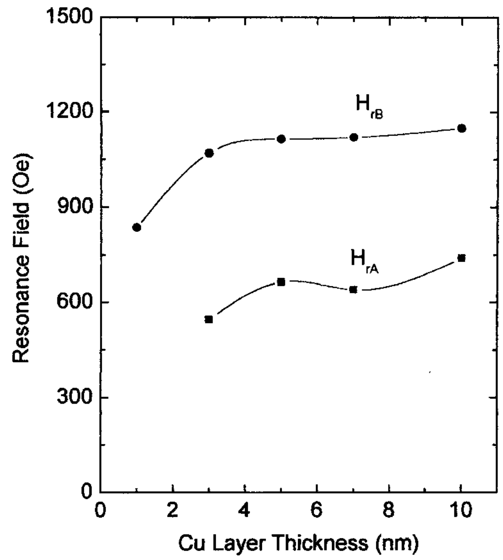

Fig. 2. Resonance field as a function of Cu layer thickness.

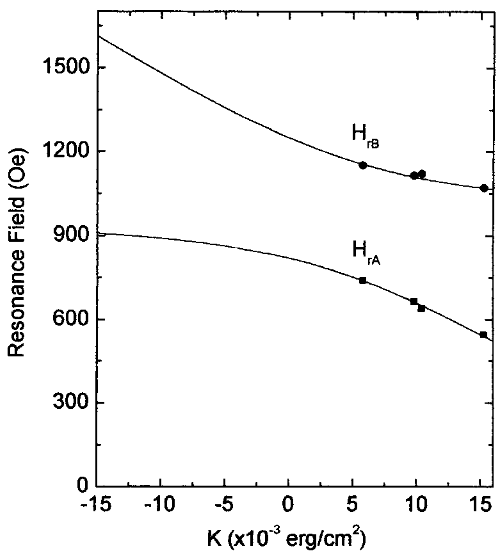

Fig. 3. The relation between resonance field and interlayer coupling constant (symbols indicate experimental values).

thickness for the CoFe (20 nm)/Cu(t_{Cu})/NiFe (20 nm) trilayer system. We can see that interlayer coupling constant decreases in an oscillatory manner as the Cu spacer thickness increases up to 10 nm. Finally, the value approaches zero above 10 nm. The coupling constant is positive for all samples. Hence, it seems that the interlayer coupling between adjacent CoFe and NiFe layers separated by a Cu layer is ferromagnetic.

4. Conclusion

In this article, the influence of the Cu spacer thickness t_{Cu} on the interlayer coupling of a CoFe (20 nm)/Cu(t_{Cu})/NiFe (20 nm) trilayer system made using DC magnetron sputtering at room temperature was studied by FMR. The interlayer coupling constant decreases in an oscillatory manner

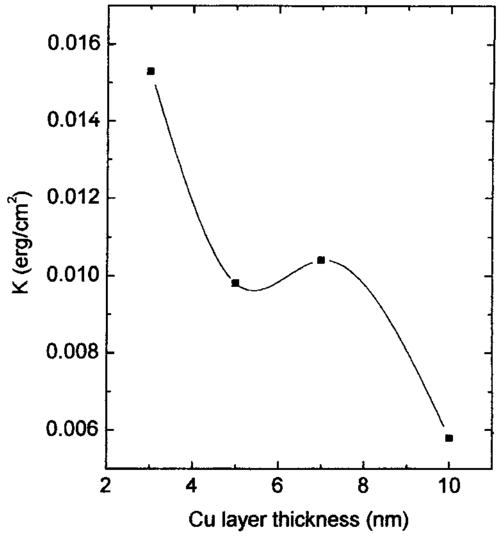

Fig. 4. Interlayer coupling constant as a function of Cu layer thickness.

as the Cu spacer thickness increases up to 10 nm. Finally, the value approaches zero above 10 nm. The coupling constant is positive for all sample. Hence, it seems that the interlayer coupling between adjacent the CoFe and the NiFe layer separated by a Cu layer is ferromagnetic.

Acknowledgments

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