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Interlayer coupling in TM (Fe, FeCo, FeCoNi) / Cu multilayers studied with FMR measurements

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Abstract

Spin wave resonance modes were observed in Fe(22 Å)/Cu(d_{Cu} Å) and FeCo(14 Å)/Cu(d_{Cu} Å) multilayers by FMR measurements, which demonstrated that spin waves propagate through nonmagnetic layers and that the multilayer film was like a single magnetic system. In FeCoNi (15 Å)/Cu(d_{Cu} Å) multilayers with Fe buffer layers, a group of resonance peaks were observed in parallel geometry.

Recently, ferromagnetic resonance (FMR) and spin wave resonance (SWR) have been used to study the effective parameters of multilayers (MLs), such as D_{eff} (the effective stiffness constant), $4\pi M_{eff}$ (effective magnetization), etc. In ML systems, the resonance condition and behavior might be more complicated than those in single-layer films, increasing the difficulty and uncertainty in interpreting the FMR data. In the present paper, some results of spin waves propagating across the magnetic–nonmagnetic structure are reported.

Fe/Cu, FeCo/Cu and FeCoNi/Cu MLs were prepared using rf sputtering, as described in previous papers [1–3]. The period determined by X-ray diffraction agreed with the designed value with a deviation of less than 5% [1]. The thickness of Cu (d_{Cu}) was varied in the range 8–45 Å, and the thicknesses of Fe, FeCo and FeCoNi were kept constant at 22, 14 and 15 Å, respectively. The saturation magnetization of the samples was measured with a VSM. The FMR spectra, at 9.7 GHz and room temperature using a Bruker EPR spectrometer, were measured as a function of different orientations of the static magnetic field H.

(1) FeCo/Cu MLs. Only one resonance peak was observed in all samples when the static field was parallel to the plane of the films. The angular dependence of the resonance field (Fig. 1) fitted well to the following expressions of uniform mode in a single-layer film:

$$H \sin(\theta_0 - \theta_H) = 4\pi M_{eff} \cos\theta_0 \sin\theta_0, \tag{1}$$

$$(\omega/\gamma)^2 = \left[H \cos(\theta_0 - \theta_H) - 4\pi M_{eff} \cos^2\theta_0\right] \times \left[H \cos(\theta_0 - \theta_H) - 4\pi M_{eff} \cos 2\theta_0\right], \tag{2}$$

where θ_H and θ_0 are the angles of H and M_5 with respect to the film normal. For perpendicular geometry, several regular resonance peaks were observed for the films with Cu thicknesses of less than 20 Å (Fig. 2). The separations between the multiple peaks were much smaller than what the standing spin wave modes across the individual magnetic layers required. However, if the multilayers were assumed to be coupled by interlayer exchange interaction into a single magnetic system and the spin waves were sustained by the whole multilayer, the resonance field of multiple peaks could be fitted to the resonance conditions similar to the single-layer films as follows:

$$\omega/\gamma = H_n^{\perp} - 4\pi M_{eff} + 2A_{eff} k_n^2/M_s, \tag{3}$$

where A_{eff} is the effective exchange constant and $k_n H = n\pi/L$. L is the total thickness of the MLs and the mode number n is an integer. $D_{eff} = 2A_{eff}/M_s h\gamma$. In fitting the

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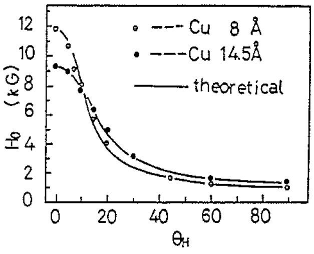

Fig. 1. Angular dependence of uniform resonance field for [FeCo(14 Å)/Cu(d_{Cu} Å)$]_{89}$ with $d_{Cu} = 8$ and 14.5 Å.

data of $H_n^{\perp}$ to the above expression, we found that n included both odd and even numbers.

Both $n = 0$ and 1 could be assigned to the strongest peak without much difference in fitting. Fig. 3 gives the relations between $H_n^{\perp}$ and n^2 for the films with $d_{Cu} = 8$, 10 and 12.5 Å. The n^2 law was obeyed for large n and a linear dispersion relation existed approximately for lower n. Based on the theory of the volume inhomogeneity model [4], as a rough approximation, we obtained the effective exchange constants $A_{eff} = 4.4 \times 10^{-7}$, 2.7×10^{-7} and 4.8×10^{-7} erg/cm for the three films. Based on the surface pinning model [6], we obtained $A_{eff} = 4.4 \times 10^{-7}$, 3.4×10^{-7} and 5.4×10^{-7} erg/cm for the same samples. These values are much smaller than the bulk values of Fe and Co. Values for the FeCo alloy are not available. The small values of A_{eff} are not unreasonable since A_{eff} is the effective value in the multilayer. Furthermore, in our sputtered multilayers, the magnetism was reduced due to the dimensional effect and alloying at the interfaces, which also led to a reduced $4\pi M_{eff}$.

(2) For Fe/Cu MLs, the FMR spectra are similar to those of FeCo/Cu MLs. The spin wave spectra were observed in perpendicular geometry [2]. D_{eff} and $4\pi M_{eff}$ were calculated to be much smaller than those of bulk iron. Assuming that the spin wave energy of the MLs is approximately equal to the spin wave energy in the total iron layers [6], then $D_{eff}k^2 = D_{Fe}k_{Fe}^2$. The phase changes of the spin waves in Cu layers were calculated; details will be published elsewhere.

(3) In FeCoNi/Cu MLs, AFM and FM coupling were observed by the oscillation of the magnetoresistance [7]. AFM-coupled [FeCoNi(15 Å)/Cu(9 Å)$]_{20}$ multilayers with Fe buffer layers had a magnetoresistance of about 35% at room temperature. Four intensive resonance peaks were observed in the sample in parallel geometry. The situation was complicated because the resonance fields were less than the saturation field. For perpendicular geometry, only one peak appeared. For FM-coupled [FeCoNi(15 Å)/Cu(13 Å)$]_{20}$ multilayers with Fe buffer layers, there were two resonance peaks in the FMR spectra for parallel geometry. The two peaks overlapped for perpendicular geometry. A detailed study is in progress.

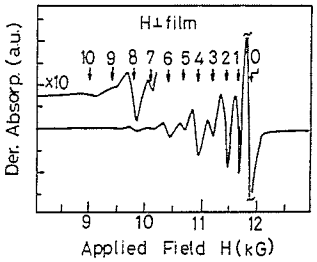

Fig. 2. FMR spectra of [FeCo(14 Å)/Cu(8 Å)$]_{89}$ multilayers for perpendicular geometry.

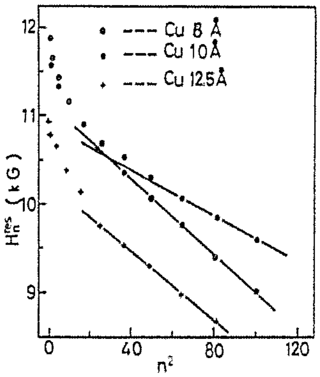

Fig. 3. Relation between $H_n^{\perp}$ and n^2 for [FeCo(14 Å)/Cu(d_{Cu} Å)$]_{89}$ multilayers with $d_{Cu} = 8$, 10 and 12.5 Å.

The resonance spectra of MLs are much more complex than those of single-layer films. To our knowledge, three mechanisms may be responsible for the appearance of interlayer coupling in FMR: (1) direct exchange interlayer interaction due to pinholes in the Cu layers; (2) indirect coupling via the induced magnetization in Cu layers; and (3) dynamic interlayer coupling [8]. Further study is needed.

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References

[1] Q.Y. Jin, Y.B. Xu, Y. Zhai, M. Lu, Q.S. Bie, S.L. Jiang and H.R. Zhai Chin, Phys. Lett. 11 (1994) 53.
[2] Y.B. Xu, M. Lu, C. Hu, Y.Z. Miao, Y. Zhai, Q.S. Bie and H.R. Zhai J. Appl. Phys. 78 (1994) 6190.
[3] M. Jimbo, T. Kanda, S. Gato, S. Tsunashima and S. Uchiyama, Jpn. J. Appl. Phys. 33 (1992) L348.
[4] A.M. Portis, Appl. Phys. Lett. 2 (1963) 6.
[5] C. Kittel, Phys. Rev. 110 (1958) 1295.
[6] P.E. Wigen, Z. Zhang, S. Iwata and T. Suzuki, J. Magn. Soc. Jpn. 15 suppl. S1 (1991) 33.
[7] M. Jimbo, S. Tusunashima, T. Kanda, S. Goto and S. Uchiyama, J. Appl. Phys. 74 (1993) 3341.
[8] H. Hurdequint and M. Malouche, J. Magn. Magn. Mater. 93 (1991) 276.