Journal of Magnetism and Magnetic Materials 140–144 (1995) 565–566

Magnetic properties and interlayer coupling of Co/Al superlattices

Q.Y. Jin [a,*], M. Lu [a], Q.S. Bie [a], Y.B. Xu [a,b,1], H.R. Zhai [a,b], Y.H. Shen [c]

[a] *Center of Materials Analysis and National Laboratory of Solid State Microstructure, Nanjing University, Nanjing 210093, China*
[b] *Center for Advanced Studies in Science and Technology of Microstructures, Nanjing 210093, China*
[c] *T.D. Lee Physics Laboratory and Department of Physics, Fudan University, Shanghai 200433, China*

Abstract

Interlayer exchange coupling in Co/Al multilayers was investigated with ferromagnetic resonance and magnetoresistance measurements. For samples with $d_{Al} \leq 19$ Å, spin waves were observed for perpendicular geometry, which implied that spin waves were sustained by the whole film and propagated through Al sublayers. Two magnetoresistance peaks corresponding to antiferromagnetic coupling between the cobalt layers were observed with increasing Al spacer thickness, but the strongest peak occurred for $d_{Al} = 23$ Å.

In recent years, the coupling of ferromagnetic metallic layers has received a great deal of attention [1,2]. Ferromagnetic layers separated by non-ferromagnetic layers can be coupled ferromagnetically (FM) or antiferromagnetically (AFM) with respect to each other. In a number of systems with the spacer of transition metals [3–6], the interlayer coupling oscillates between FM and AFM as the thickness of the nonmagnetic layer varies. This oscillatory behavior has also been obtained in Fe/Al and Fe/Al/Fe systems [7,8], in which Al is a simple metal with the exchange correlation integral and the density of states (DOS) similar to those of copper. We report here the results of our studies of Co/Al multilayers by magnetoresistance (MR) and ferromagnetic resonance (FMR).

The Co/Al multilayers were prepared by rf sputtering in a system with a base pressure of 3×10^{-6} Torr. An argon gas pressure of 4 mTorr was used during deposition. The multilayer structure was achieved by rotating the water-cooled substrate and alternately exposing it to each of the two targets. The deposition rates of Co and Al were 1.2 and 0.7 Å/s, respectively. Single silicon substrates were used. Low- and high-angle X-ray diffraction confirmed the films to be well periodically layered, and polycrystalline with Al(200), Co(111) orientation texture. Fig. 1 shows the low-angle X-ray diffraction pattern of the Co(30 Å)/Al (16 Å) multilayer film.

The anisotropy of the films was measured by a torque meter with a magnetic field of 2 T at room temperature. For the samples with a constant Al layer thickness of 15 Å and various Co layer thicknesses, the interfacial anisotropy constant was determined to be as high as 0.68 erg/cm^2. The value is very large compared with the value of Mitsuzuka et al. [9] of 0.25 erg/cm^2. They found that their Co/Al multilayers had significant Co–Al alloying at the interfaces with a reduced value of saturation magnetization. This suggests relatively sharp interfaces and less interdiffusion in our Co/Al samples.

The FMR measurements were performed using an ER200D-SRC EPR spectrometer with X-band microwave frequency of 9.778 GHz. It was conducted at room temperature with different orientations of the external magnetic field with respect to the film plane. The magnetoresistance (MR) measurements were carried out at room temperature using a standard four-point apparatus with a maximum magnetic field of 8 KOe. The samples for the FMR and MR measurements were Co(30 Å)/Al(d_{Al}) with d_{Al}, the thickness of Al, varying from 8 to 28 Å.

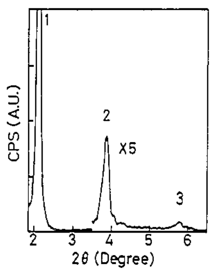

Fig. 1. Low-angle X-ray diffraction pattern of a Co(30 Å)/Al(16 Å) multilayer film.

* Corresponding author. Present address: Department of Physics, Fudan University, Shanghai 200433, China.
[1] Present address: Department of Physics, University of Leeds, Leeds, UK.

SSDI 0304-8853(94)00550-8

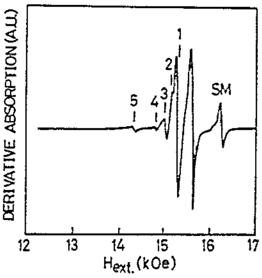

Fig. 2. A typical perpendicular FMR spectrum of the sample with $d_{Al} = 8$ Å.

In FMR, when the magnetic field was parallel to the film plane, only one resonance peak related to the uniform mode appeared. When the field was applied perpendicular to the film plane, multiples resonance peak spectra were observed for the samples with $d_{Al} < 19$ Å, but only one peak for $d_{Al} > 19$ Å. A typical perpendicular FMR spectrum of the sample with $d_{Al} = 8$ Å was shown in Fig. 2. By carefully analyzing the spectrum, we found that the signals marked 1–5 in the figure corresponded to the spin waves with modes $n = 1, 2, 3, 4, 5$ and the signal next to $n = 1$ to the uniform mode with $n = 0$. The intensities of spin waves with even n looked weaker than those of spin waves with odd n. The resonance field H_{res} obeyed the so-called n^2 law, as shown in Fig. 3.

The excitation of spin waves implies that the multilayers are coupled by the interlayer exchange interaction into a single magnetic system, and the standing spin waves with different wavelengths are sustained by the whole film thickness instead of by individual Co layers. Thus the spin waves can propagate through Al sublayers. The appearance of spin wave modes with odd and even n may be understood as being due to inhomogeneities in the multilayers. The resonance peak on the high-field side may correspond to a surface mode, but further quantitative studies are needed.

Fig. 4 shows the MR ratio curve as a function of d_{Al}. The oscillatory magnetoresistance showed a period of 13 Å, the same order as the period reported for many other systems, which indicated the oscillatory interlayer coupling from FM to AFM when the Al thickness was varied.

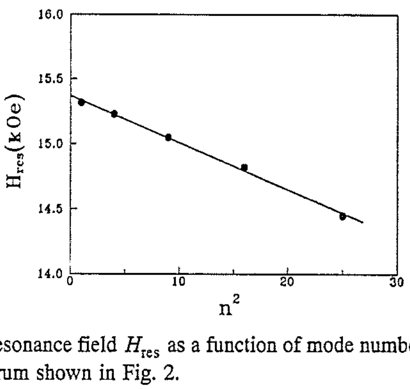

Fig. 3. Resonance field H_{res} as a function of mode number n from the spectrum shown in Fig. 2.

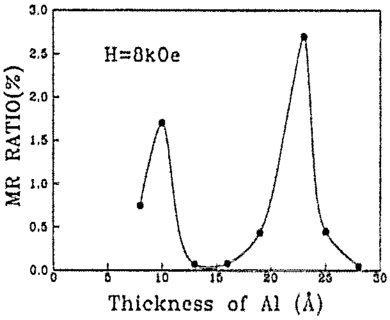

Fig. 4. Magnetoresistance ratio $\Delta R/R_s$ curve versus Al spacer layer thickness. The external magnetic field applied is 8 kOe in the film plane.

However, the highest MR peak appeared at 23 Å instead of around 10 Å (1.7% for $d_{Al} = 10$ Å and 2.7% for $d_{Al} = 23$ Å). Similar behavior has been reported by other authors, and is considered to be associated with the occurrence of a certain unfavorable microstructure for small d_{Al}.

In conclusion, the magnetic properties and interlayer coupling in Co/Al multilayers made by rf sputtering have been investigated. Oscillatory MR was obtained, indicating oscillations between FM and AFM coupling with changing Al layer thicknesses from 8 to 28 Å. But spin waves in perpendicular FMR were observed only for samples with Al thicknesses of less than 19 Å. This suggests that in order to observe the spin wave resonance, higher interlayer exchange coupling is needed. No clear difference between spin waves in FM and AFM coupled systems was found.

Acknowledgements: This work was supported by the National Nature Science Foundation (NNSF), the State Education Commission (SEC) of China and the National Key Laboratory of Magnetism, Academia Sinica.

References

[1] P. Grünberg, R. Schreiber, Y. Pang, M.B. Brodsky and H. Sowers, Phys. Rev. Lett. 57 (1986) 244.
[2] B. Heinrich, Z. Celinski, J.F. Cochran, W.B. Muir, J. Rudd, Q.M. Zhong, A.S. Arrott, K. Myrtle and J. Kirschner, Phys. Rev. Lett. 64 (1990) 673.
[3] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Fiederich and J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.
[4] S.S.P. Parkin, N. More and K.P. Roche, Phys. Rev. Lett. 64 (1990) 2304.
[5] D.J. Keavney, D.F. Storm, J.W. Freeland, M.D. Wieczorek, J.C. Walker, M.G. Pini, P. Politi and A. Rettori, Phys. Rev. Lett. 71 (1993) 727.
[6] V. Grolier, D. Renard, B. Bartenlian, P. Beauvillain, C. Chappert, C. Dupas, J. Ferré, M. Galtier, E. Kolb, M. Mulloy, J.P. Renard and P. Veillet, Phys. Rev. Lett. 71 (1993) 3023.
[7] A. Fuß, S. Demokritov, P. Grünberg and W. Zinn, J. Magn. Magn. Mater. 103 (1992) L221.
[8] C.J. Gutierrez, J.J. Krebs, M.E. Fillipkowski and G.A. Prinz, J. Magn. Magn. Mater. 116 (1992) L305.
[9] T. Mitsuzuka, A. Kamijo and H. Igarashi, J. Appl. Phys. 68 (1990) 1787.