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Spin polarization of nonmagnetic layers in multilayers

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Abstract

Magnetic measurements, ferromagnetic resonance, magneto-optical Kerr rotation and nuclear magnetic resonance have been used to study the spin polarization of nonmagnetic layers of Pd, Cu, Ag and Al in multilayers and sandwiches containing Fe, Co, FeCo and CoCr. The existence of the spin polarization of Pd, Cu, Ag and Al was demonstrated directly or indirectly.

In all theories on the interlayer exchange interaction in ferromagnetic/nonmagnetic (FM/HM) multilayers (MLs), the existence of spin polarization (SP) of the NM layers is considered implicitly or explicitly. Thus, the experimental study of the SP of NM layers is an important topic, but is difficult because of its weakness. So far, only a few papers have dealt with this problem [1–3], and all of them used experimental techniques that are difficult to access. We have tried to study this problem using several ordinary methods available in our laboratory. To our surprise, some interesting results have been obtained, which are briefly described in this paper.

(1) *Magnetic and ferromagnetic resonance* (FMR) *measurements*: The magnetization measured by a vibrating sample magnetometer, M_{VSM}, includes a contribution from the SP of NM layers and is defined as $M_{VSM} = M_{FM} + M_{NM} d_{NM}/d_{FM}$. The effective magnetization M_{eff} determined by FMR, on the other hand, does not include the contribution of the SP of NM layers, being defined as $4\pi M_{eff} = 4\pi M_{FM} - H_K$, in which the anisotropy field $H_K = 2K/M_{FM}$. By magnetic torque curve measurements the effective anisotropy constant $K_{eff} = K - 2\pi M_{VSM}^2$ can be determined. From the above data, the spin polarization of Pd layers in Fe/Pd MLs and of Cu layers in Co/Cu MLs, and their dependence on the NM layer thickness d_{NM} were determined: Pd ≈ 0.5 μ_B/atom, Cu ≈ 0.09 μ_B/atom. Both of these values decrease with increasing d_{NM} [4,5]. Fig. 1 shows the induced magnetization of Cu layers in Co(22 Å)/Cu(d Å) MLs.

(2) *Magneto-optical Kerr rotation (MOKR) spectra measurements*: The MOKR spectra of Fe/Pd, FeSi/Cu [4], Fe/Ag [6], and Co/Cu [5] were measured and compared with the spectra calculated numerically based on Fresnel equations for multilayers [4] without considering the effect of interlayer coupling. Anomalous behaviour in the experimental spectra was found, in contradiction with the calculated spectra when d_{NM} was small. A theoretical model calculation of the additional MOKR created by the spin polarization of NM layers explained the discrepancies. For Fe/Ag MLs the MOKR spectrum calculated in such a way agreed well with the experimental one [6]. In Fe/Ag and FeSi/Cu MLs, negative SP of Ag and Cu was assumed, while in Fe/Pd and Co/Cu MLs, positive SP was needed. In Ref. [1] a postive SP in Co/Cu was also found. In addition, it was found that in a number of sandwiches such as CoCr/Cu, Ag, Al/CoCr [7], FeCo/Cu/FeCo and Co/Al/Co, the MOKR oscillated with changing d_{NM}. The periods ranged from 13 to 20 Å. This kind of oscillation may be due to the oscillation of the SP of NM layers

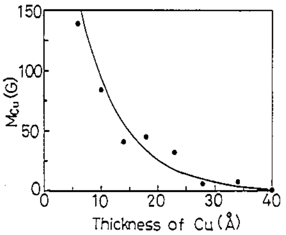

Fig. 1. Magnetization of Cu as a function of d_{Cu}.

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which was found in Co/Cu layers by MXD [1], or due to the oscillation of the magnetization in ferromagnetic layers.

(3) *Spin wave resonance (SWR) and coupled modes*: Multiple peaks of SWR were observed in Fe/Cu, FeCo/Cu and Co/Al [8,9] MLs. Their behaviour could be described approximately with the theory of SWR in single-layer films. The multilayers were assumed to be a coupled single magnetic system and the excited spin waves were sustained by the whole multilayer thickness. By fitting the fields of SWR H_{ros} with the resonance condition of the single-layer film, it was found that the resonance peaks corresponded to spin waves with both odd and even mode numbers, and that a square dispersion relation $H_{ros} - n^2$ existed, from which the effective exchange constant could be determined. It was also found that spin waves propagated through the whole film thickness and that the FM and NM layers shared the total phase change. All of these findings gave interesting information on the interlayer coupling and the spin polarization of NM layers.

In some multilayers, such as the Co/Cu system, no SWR was observed in our laboratory even when the Cu layer thickness was as low as 6 Å. However, a weak extra peak on the high-field side was observed in the MLs with small d_{Cu}. From the angular and thickness dependence of the peak position and intensity, we think it may correspond to a kind of coupled mode [10].

(4) *Nuclear magnetic resonance (NMR) of nuclei in NM layers*: The NMR of ^{63}Cu and ^{65}Cu nuclei in Fe/Cu MLs were performed with a Bruker MSL-300 spectrometer. High sensitivity was achieved by using a pulse-echo and Fourier transformation method with the number of scans up to 10^6–10^7. A group of satellite peaks was found in the NMR spectra on both sides of the pure copper resonance peak, as shown in Fig. 2. The satellite peaks were considered as a result of non-uniform spin polarization of the conduction elections in Cu layers caused by exchange coupling with Fe layers. From the position of the multiple peaks, we obtained the additional Knight shift and also the additional effective field experienced by the spin of conduction electrons or the exchange field H_{BX}, which showed oscillatory behaviour. To our knowledge, this is the first report of direct evidence of the oscillatory distribution of SP and the related exchange field in Cu layers of multilayers [11,12].

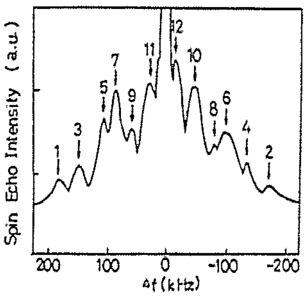

Fig. 2. Spin-echo spectrum of ^{63}Cu nuclei in [Fe(60 Å)/Cu(25 Å)]$_{50}$ multilayers deposited on a Kapton substrate.

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References

[1] J.-F. Bobo, M. Piecuch, S. Pizzini, A. Fontaine, E. Dartyge, Ch. Giorgetti and F. Baudelet, J. Magn. Magn. Mater. 126 (1993) 251.
[2] C. Carbone, E. Vescove, O. Rader, W. Gudat and W. Eberhardt, Phys. Rev. Lett. 71 (1993) 2805.
[3] K. Garrison, Y. Chang and P.D. Johnson, Phys. Rev. Lett. 71 (1993) 2801.
[4] H.R. Zhai, M. Lu, Y.Z. Miao, Y.B. Xu, S.M. Zhou, H. Wang, J.W. Cai, B.X. Gu, S.L. Zhang and H.Y. Zhang, J. Magn. Magn. Mater. 115 (1992) 20.
[5] M. Lu, Q.S. Bie, Y.B. Xu, Q.Y. Jin, Y. Zhai, S.L. Jiang, X.B. Zhu and H.R. Zhai, J. Magn. Magn. Mater. 140–144 (1995) 581 (these Proceedings).
[6] Y.B. Xu, H.R. Zhai, M. Lu, Q.Y. Jin and Y.Z. Miao, Phys. Lett. A 168 (1992) 213.
[7] Q.Y. Jin, H.R. Zhai, Y.B. Xu, Q.S. Bie, M. Lu and Y.H. Shen, J. Magn. Magn. Mater. 140–144 (1995) 1985 (these Proceedings).
[8] H.R. Zhai, X.B. Zhu, M. Lu, Q.S. Bie, Y.B. Xu, Y. Zhai, Q.Y. Jin, M. Jimbo and S. Tunashima, J. Magn. Magn. Mater. 140–144 (1995) 525 (these Proceedings).
[9] Q.Y. Jin, M. Lu, Q.S. Bie, Y.B. Xu, H.R. Zhai and Y.H. Shen, J. Magn. Magn. Mater. 140–144 (1995) 565 (these Proceedings).
[10] B. Heinrich, Z. Celincki, K. Myrtle, J.F. Cochran, A.S. Arrott and J. Kirschner, J. Magn. Magn. Mater. 93 (1991) 75.
[11] Q.Y. Jin, Y.B. Xu, H.R. Zhai, C. Hu, M. Lu, Y. Zhai, G.L. Dunifer, H. Naik and M. Ahmad, J. Magn. Magn. Mater. 126 (1993) 285.
[12] Q.Y. Jin, Y.B. Xu, H.R. Zhai, C. Hu, M. Lu, Q.S. Bie, Y. Zhai, G.L. Dunifer, H. Naik and M. Ahmad, Phys. Rev. Lett. 72 (1994) 768.