Domain wall theory and exchange stiffness in Co/Pd multilayers

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Abstract

The stripe model of domain structure in multilayers is studied by micromagnetic simulation. The results indicate a strong reduction of the effective domain wall energy (by dipolar effects). Domain width measurements on sputtered Co/Pd multilayers are compared with the theory. The estimated exchange stiffness is comparable with that of bulk Co. The effects of interface roughness and of interlayer exchange are discussed.

Keywords: Multilayers; Exchange; Domain walls

Domain structures in magnetic multilayers (MLs) with perpendicular anisotropy may attract interest for two main reasons: the tendency to spontaneous domain formation needs to be known and controlled in recording applications, and comparisons of the observed structures with appropriate models may be used to study the exchange stiffness. This paper has the latter motive. We extend the stripe-domain model [1] including the real wall structure (using fine finite elements), and compare the theory and experimental results on sputtered Co/Pd MLs [2,3] including new data; the estimated exchange stiffness fitting of the results is compared with bulk values [4].

The stripe domain model consisting of straight domains of alternating mean magnetization direction ('up' and 'down' along the film normal) for MLs has so far been used in its 'classical' or 'rigid' version [1], where the magnetization is uniform in each domain and the walls are treated as ideal planar boundaries endowed with constant surface energy densities. The predicted dependence [3] of the equilibrium domain width D on the total ML thickness T closely follows a single 'universal' curve if both D and T are scaled by the characteristic length

$$l^* = 4\sqrt{A^*K_u^*}/\mu_0 M_s^{*2}, \quad (1)$$

where $M_s^* = fM_s$, $K_u^* = fK_u$ and $A^* = fA$ are, respectively, the saturation magnetization, the uniaxial anisotropy constant and the (in-plane) exchange stiffness assigned to the ML as a whole, while M_s , K_u and A are the respec-

tive constants assigned to the magnetic layers of thickness t_m (separated by spacer layers of thickness t_s), and $f = t_m/(t_m + t_s)$ is the filling factor. The 'universal' line (U in Fig. 1a,b) was obtained earlier [5] for uniform films ($f = 1$). However, the Bloch wall structure assumed in Eq. (1) is not stable and the flux-closing (Néel wall) structure has lower energy [6]. This effect is enhanced [7,8] by the lack of interlayer exchange in the ML. Thus realistic models should predict finer domains than the 'rigid' stripe model.

We have now investigated the stripe model 'micromagnetically', simulating the *entire* magnetic structure by periodic arrays of fine, uniformly magnetized elements shaped as square rods, with sides equal to t_m (1–4 atoms), and seeking equilibrium by iterative relaxation. The results are illustrated in Fig. 1(a) as the scaled dependence of D/l^* on T/l^* , for three values of the quality factor of the magnetic layers, $Q = 2K_u/\mu_0 M_s^2$. These predictions are indeed far from those of the 'rigid' model (U line). As shown in Fig. 1(b), almost universal scaling is approximately restored when an effective characteristic length is used for the scaling:

$$l_{\text{eff}}^* = 4\sqrt{A^*K_{\text{eff}}^*}/\mu_0 M_s^{*2}, \quad (2)$$

where $K_{\text{eff}}^* = f(K_u - 0.5\mu_0 M_s^2)$ is the effective (directly measured) anisotropy constant. The 'universality' breaks down when $Q \rightarrow l$ or $D \rightarrow T$, and cannot be used for precise fitting.

More specific model results were compared with our measurements of domain widths in demagnetized Co/Pd MLs prepared by rf sputtering in Ar, and characterized magnetically by VSM and torque measurements [2]. The average domain widths were measured by the colloid-SEM

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Fig. 1. Dependence of the domain width D on the multilayer thickness T predicted by the stripe model with realistic wall structure for 3 parameter sets: (1) $Q = 2.2$, $f = 0.55$, (2) $Q = 1.2$, $f = 0.55$, (3) $Q = 1.1$, $f = 0.275$, compared with the curve (U) obtained earlier for uniform films and 'rigid' magnetization (infinite Q). D and T are scaled by factors (a) l^* (Eq. (1)), and (b) l_{eff}^* (Eq. (2)).

method and by MFM. Table 1 presents our earlier data [3], and new results for two thin MLs with very flat domains. The micromagnetic model was used for each set of ML structure and magnetic parameters. With D oscillating around the experimental D_0 , the exchange stiffness constant A was changed until D_0 corresponded to the minimum of total energy. The resulting A values, also presented in Table 1, are much larger than our earlier ('rigid'

Table 1

Data on the Co/Pd ML structure, magnetization and anisotropy (per Co volume), domain width and in-plane exchange stiffness from the model fitting. The numbers of bilayers are 25 and 7 in samples (rows) 1–4 and 5–6, respectively

t_{Co} (nm)	t_{Pd} (nm)	M_s (kA/m)	K_{eff} (kJ/m ³)	D (nm)	A (pJ/m)
0.85	1.4	1850	40	90	31
0.43	2.9	1580	1550	145	2.3
0.45	1.4	2026	1006	135	24
0.23	1.4	2445	1615	185	29
0.40	1.1	2100	360	220	25
0.40	1.1	1780	300	280	15

model) estimates [3]. The value from neutron diffraction on bulk Co [4] is 30 pJ/m.

In the last four samples (rows) in Table 1, the variation of A correlates with that of M_s , and the latter exceeds that of bulk Co, which indicates distribution of both the magnetic moments and the lateral exchange stiffness over magnetic thickness t_m exceeding the nominal t_{Co} . This view is supported by X-ray diffraction data [2] and also by recent pattern-recognition analysis of XPS data [9], which indicate considerable interface roughness in our MLs. Such broadening of the magnetic layer profiles was also simulated in the present model. As long as the macroscopic (measured) T , K_{eff}^* and M_s^* (and thus l_{eff}^*) are kept constant (which is the case for curves 2 and 3 in Fig. 1), the predicted domain size does not practically change (as seen in Fig. 1b).

The remarkably low value of A obtained for the sample with the largest Pd thickness, exceeding the margin of 2 nm which seems to be the limit for interlayer exchange coupling (IEC) in Co/Pd MLs [10], raises the question of the possible role of the IEC in the domain structures. A large IEC would inhibit the flux closure reducing the wall energy. This was also verified in our model: we varied the ratio of the IEC to the in-plane exchange coupling and found that the effective wall energy (or characteristic length [6]) increases rapidly between the values 0 and 0.1 for this ratio, and remains constant thereafter. Thus a lower in-plane exchange coupling would be needed to fit the experiments with a large IEC added to the model. The present one-parameter fitting thus calls for extension to include variations in the domain width in MLs with varying IEC (i.e. spacer layer thickness or composition).

Acknowledgements: The computations on the Cray Y-MP EL at the Institute of Physics in Prague were supported financially by Westinghouse Electric Co.

References

- [1] A. Suna, J. Appl. Phys. 59 (1987) 313.
- [2] P. de Haan, Q. Meng, T. Katayama and J.C. Lodder, J. Magn. Magn. Mater. 113 (1992) 29.
- [3] J. Šimšová, R. Gemperle, V. Kamberský, S. Porthun, P. de Haan and J.C. Lodder, IEEE Trans. Magn. 30 (1994) 784.
- [4] H.A. Alperin, O. Steinsvoll, G. Shirane and R. Nathans, J. Appl. Phys. 37 (1966) 1052.
- [5] Z. Málek and V. Kamberský, Czech. J. Phys. 8 (1958) 416.
- [6] T.G.W. Blake, C.C. Shir, Y.O. Tu and E. Della Torre, IEEE Trans. Magn. 18 (1982) 985.
- [7] R. Ploessl, J.N. Chapman, M.R. Scheinfein, J.L. Blue, M. Mansuripur and H. Hoffmann, J. Appl. Phys. 74 (1993) 7431.
- [8] V. Kamberský, J. Magn. Soc. Jpn. 19 Suppl. S-1 (1995) 37.
- [9] B. Lesiak, J. Zemek, P. de Haan and A. Jozwik, Surf. Sci. 346 (1995) 79.
- [10] W.R. Bennett, C.D. England, D.C. Person and C.M. Falco, J. Appl. Phys. 69 (1991) 4384.