ISSN 1063-7850, Technical Physics Letters, 2014, Vol. 40, No. 3, pp. 245–248. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © G.I. Frolov, S.Ya. Kiparisov, V.A. Seredkin, K.P. Polyakova, G.S. Patrin, V.S. Zhigalov, A.D. Balaev, 2014, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2014, Vol. 40, No. 6, pp. 28–34.

Peculiarities of Magnetization Reversal in Exchange-Coupled Ferro/Ferromagnet NiFe/CoP Film Structures

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Received October 25, 2013

Abstract—The effect of layer thicknesses on the magnetic properties and mechanism of magnetization reversal in exchange-coupled NiFe/CoP film structures has been studied. The process of magnetization reversal was studied by analysis of the magnetic-induction and magneto-optical hysteresis loops. It is established that, as the thicknesses of layers in the NiFe/CoP film structure are increased, the system exhibits a transition from homogeneous magnetization reversal in the structure to exchange spring formation in the soft magnetic layer.

DOI: 10.1134/S1063785014030286

Exchange-coupled magnetic-film structures consisting of soft- and hard-magnet layers are of considerable interest for both basic science and numerous applications [1–4]. In recent years, much attention has been devoted, in addition to ferro/antiferromagnet and ferro/ferromagnet systems, to ferro/ferromagnet exchange-coupled film structures. This interest is explained by the discovery of alternative magnetization-reversal mechanisms in these systems [5, 6].

A model of magnetization reversal in ferro/ferromagnet exchange-coupled film structures was proposed as long ago as 1965 (see, e.g., [7]). Assuming that the hard magnetic layer is strongly anisotropic while the soft magnetic layer is isotropic, the magnetizations of the two layers in the initial state are parallel. This state of the layered structure is retained in switching magnetic fields below exchange field H_{ex} that is defined by the formula

$$H_{ex} = \pi^2 A/2M_s t_s^n, \quad (1)$$

where A is the exchange parameter, M_s is the saturation magnetization, t_s is the magnetic-layer thickness, and $n = 2$.

In magnetic fields $H > H_{ex}$, a spin helix appears in the soft magnetic layer, in which the angle of spin rotation increases with the distance from the interface. The multistep mechanism of magnetization reversal involves the processes of domain-wall formation and propagation in depth of the soft layer. The magnetization of this layer exhibits reversal in fields $H < H_{ch}$, where H_{ch} is the coercivity of the hard magnetic layer.

Experimental investigations confirmed the validity of this model in general, but also revealed some discrepancies. First, it was found that $n < 2$ in structures with soft magnetic-layer thicknesses $t_s > 50$ nm. Second, in structures with $t_s < \pi\delta_h$ (where $\pi\delta_h$ is the domain wall width in the hard layer), both layers exhibit simultaneous magnetization reversal in fields $H < H_{ch}$. The magnitude of the magnetization-reversal field depends on the thicknesses of layers, which implies that the interlayer exchange in these structures leads to modification of the properties of both layers.

Thus, calculations based on the model of spin helix formation could only qualitatively explain peculiarities of the magnetization-reversal process in ferro/ferromagnet exchange-coupled film structures. To adequately describe the properties of these materials, it is necessary to carry out additional investigations involving additional methods for the characterization of samples and a wider circle of structures.

For purposes of expanding the set of analytical methods, it would be of interest to study the mechanisms of magnetization reversal separately in each layer (e.g., using magneto-optic techniques) and thoroughly trace the shift of the individual hysteresis loop during magnetization reversal in the soft magnetic layer alone.

In this context, we have studied the mechanisms of magnetization reversal in a ferro/ferromagnet exchange-coupled bilayer film structure consisting of hard magnetic (CoP) and soft magnetic (NiFe) layers of various thicknesses. The CoP layer was formed by chemical deposition, while the permalloy layer was

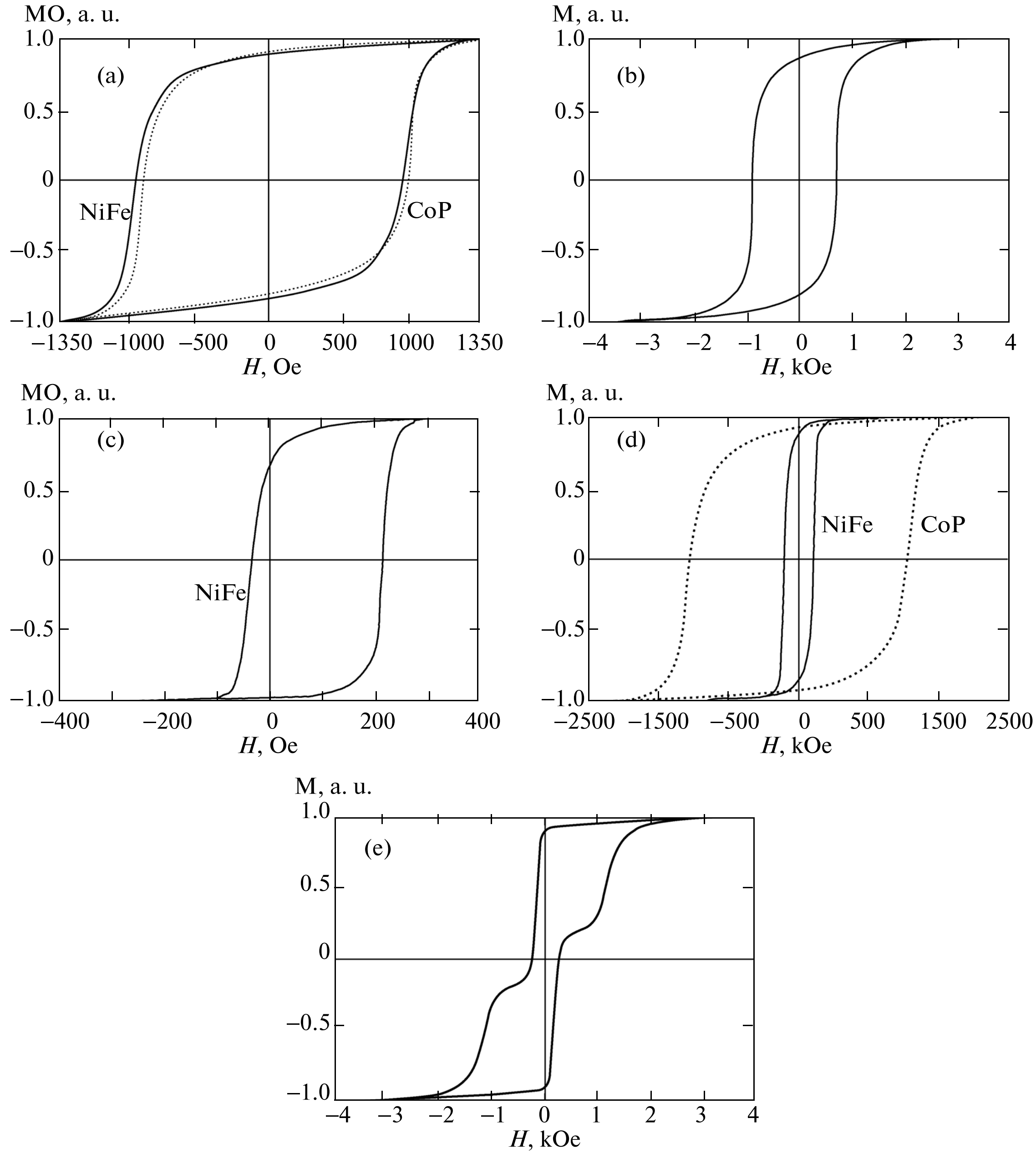

Fig. 1. Magneto-optic (MO) and magnetic-induction (M) hysteresis loops for NiFe/CoP film structures with various thicknesses of layers: (a, b) NiFe 20 nm/CoP 20 nm; (c, d, e) NiFe 50 nm/CoP 25 nm.

obtained by thermal deposition in vacuum. It has been previously established [8] that CoP films with a phosphorus content of ~2.5 wt % and thicknesses within 50 nm possess a fine-grained structure, with the hexagonal *c* axis of grains oriented predominantly perpendicular to the film plane.

The samples had a saturation magnetization of $M_s \sim 1400$ G and were in-plane isotropic with a coercivity of $H_C > 1000$ Oe. The hysteresis loops were measured by the magnetic-induction and magneto-optic techniques. Using the magneto-optic Kerr effect, it is possible to measure the individual hysteresis loops for each layer of the structure, which provides additional information on the mechanisms of the magnetization-reversal process. All measurements were performed at room temperature. The thicknesses of layers in the structure were varied within 2.5–40 nm for CoP and 20–150 nm for NiFe.

Figure 1 presents the typical magneto-optic and magnetic-induction hysteresis loops measured for the magnetization reversal along the easy axis of NiFe/CoP film structures with various thicknesses of layers. In this case, the easy axis direction is determined by the direction of magnetization in the hard magnetic layer. The hysteresis loops in Figs. 1a and 1b refer to a sample with both NiFe and CoP layer thicknesses of 20 nm. The magneto-optic loops of each layer (Fig. 1a) and the magnetic-induction loop of the entire structure (Fig. 1b) are identical, indicating that the magnetic moments of thin NiFe and CoP layers are strongly coupled and the system exhibits magnetization reversal as a whole. The coercivity of this structure was $H_C \sim 830$ Oe, while the 20-nm-thick reference CoP film had a coercivity of $H_C \sim 1300$ Oe.

In the structure with NiFe and CoP layer thicknesses of 50 and 25 nm, respectively, the soft magnetic layer exhibited unidirectional anisotropy ($H_E \sim 90$ Oe) for magnetization reversal at $H = 300$ Oe (Fig. 1c), but the loop measured at $H = 1500$ Oe was already symmetric (Fig. 1d). The latter field also produced magnetization reversal in the hard magnetic layer (Figs. 1d and 1e). Thus, the magnetization reversal in component layers of this film structure takes place in different fields and the loop of the soft layer measured at $H < H_{ch}$ is shifted along the H axis. The data in Fig. 1 show that, as the thicknesses of layers are increased, the mechanism of magnetization reversal changes from homogeneous magnetization reversal in the whole structure to separate magnetization reversal in the two layers at different fields.

In order to trace the peculiarities of this transition, let us consider the influence of the thickness of each layer on the magnetic properties of the structure. Figure 2 shows how the magnetic properties of a 100-nm-thick NiFe layer change when the thickness of the hard magnetic layer is varied within 2.5–30 nm. For structures with CoP layer thicknesses below 10 nm, H_E sharply decreases and the unidirectional anisotropy vanishes at $t_{CoP} = 2.5$ nm. At the same time, the coercivity of the permalloy layer increases almost linearly with t_{CoP} varied within 2.5–10 nm. These results are analogous to those reported for exchange-coupled ferro/antiferromagnet bilayer structures [2, 9].

Data on the variation of H_E and H_C of the soft magnetic layer in structures with a constant CoP layer thickness (20 nm) and the permalloy layer thickness varied from $t_{FeNi} = 20$ to 150 nm are presented in the table. These results show that the structures with $t_{FeNi} < 50$ nm possess no unidirectional anisotropy and exhibit a large coercivity. At $t_{FeNi} \geq 50$ nm, there appears a shift H_E of the hysteresis loop, the magnitude of which is equivalent to the field of spin spring nucleation and depends on the soft-magnetic layer thickness as

$$H_E = H_{N0}/(t_{NiFe})^n, \quad (2)$$

where $1 < n < 2$ and $N_{N0} = \pi^2 A/2M_s$ (for the NiFe layer).

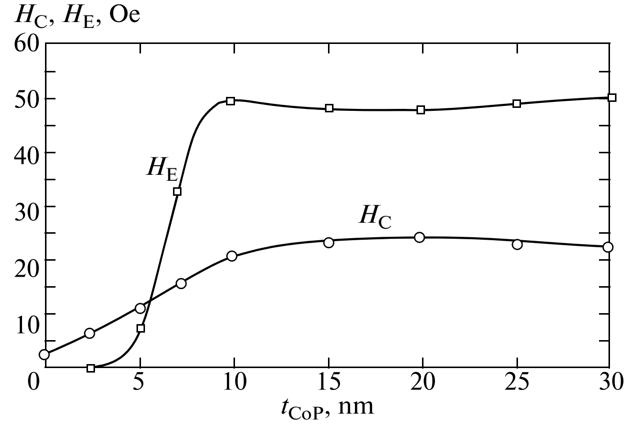

Fig. 2. Dependences of the hysteresis loop shift (H_E) and coercivity (H_C) on the thickness of the CoP layer in NiFe/CoP film structures ($t_{NiFe} = 100$ nm).

In order to calculate the coercivity of a ferro/antiferromagnet film structure in which both layers exhibit simultaneous magnetization reversal, Yan et al. [6] proposed the following equation:

$$H_C = H_{Co}t_{eh}/(t_{eh} + \alpha t_{es}), \quad (3)$$

where H_{Co} is the coercivity of the free hard magnetic layer with thickness t_h; $\alpha = M_s/M_h$; M_s and M_h are the magnetizations of the soft and hard magnetic layers, respectively; and t_{eh} and t_{es} are the effective thicknesses of the soft and hard magnetic layers, respectively. Here, the t_{eh} and t_{es} values are equal to real thicknesses (t_h and t_s) of the corresponding layers, provided that t_h, $t_s < l_{ex}$, where l_{ex} is the exchange interaction length. In this case, this condition is only valid for sample No. 1 (see table), in which the measured H_C coincides with the calculated value. For sample No. 2, calculated coercivity $H_C \approx 600$ Oe exceeds the experimental values.

Thus, we have studied the effect of layer thicknesses on the magnetic properties and mechanism of magnetization reversal in the exchange-coupled NiFe/CoP film structure. The results qualitatively agree with those reported for SmFe/NiFe and SmCo/Fe bilayers [1, 6], according to which the film structures with

Hysteresis loop shift H_E and coercivity H_C of NiFe layers with various thicknesses in NiFe/CoP structures (t_{CoP} = 20 nm)

Sample no.	t_{NiFe}, Å	H_E, Oe	H_C, Oe
1	200	–	830
2	400	–	400
3	600	110	90
4	1000	47	23
5	1500	23	13

increasing layer thicknesses exhibit a transition from homogeneous magnetization-reversal process to magnetization reversal in individual layers in different magnetic fields.

However, for detailed description of the mechanisms of magnetization reversal in exchange-coupled hard/soft film structures, it is necessary to additionally study the intermediate interval of layer thicknesses $\pi\delta_h < t_s < 2\pi\delta_h$, where $\pi\delta_h$ is the domain wall width in the hard magnetic layer. This will ensure more correct determination of parameter n in Eq. (2) and the condition of applicability of Eq. (3).

REFERENCES

1. E. E. Fullerton, J. S. Jiang, M. Grimsditch, et al., Phys. Rev. B **58**, 12193 (1998).
2. H. Xi and R. M. White, Phys. Rev. B **61**, 80 (2000).
3. Yu. P. Kabanov and V. S. Gornakov, Tech. Phys. Lett. **29**, 178 (2003).
4. G. I. Frolov, V. A. Seredkin, and V. Yu. Yakovchuk, Tech. Phys. Lett. **36**, 57 (2010).
5. T. Leineweber and H. Kronmiller, J. Magn. Magn. Mater. **176**, 145 (1997).
6. S. Yan, J. A. Barnard, F. Xu, et al., Phys. Rev. B **64**, 184403 (2001).
7. E. Goto, N. Hayashi, T. Miyashita, and K. Nakagawa, J. Appl. Phys. **36**, 2951 (1965).
8. V. V. Vershinin, S. Ya. Kiparisov, G. S. Patrin, S. M. Zharkov, and K. P. Polyakova, Phys. Met. Metallogr. **103**, 466 (2007).
9. D. Mauri, H. C. Siegman, P. S. Bagues, and E. Kay, J. Appl. Phys. **62**, 3047 (1987).

Translated by P. Pozdeev