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MAGNETISM AND FERROELECTRICITY

Magnetic Aftereffect in Co–P Trilayer Films

G. S. Patrin[a, b], **A. V. Chzhan**[a, b, *], **S. Ya. Kiparisov**[a], **V. A. Seredkin**[a], and **M. G. Pal'chik**[b]
[a] *Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences,*
Akademgorodok, Krasnoyarsk, 660036 Russia
** e-mail: avchz@mail.ru*
[b] *Siberian Federal University, pr. Svobodny 79, Krasnoyarsk, 660041 Russia*

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Abstract—This paper reports on the results of experimental investigations of the magnetic properties of a trilayer system that consists of high-coercive polycrystalline and low-coercive amorphous magnetic Co–P layers and a nonmagnetic amorphous Ni–P interlayer. It has been established that the coercive force and the bias field of the hysteresis loop of the low-coercive layer undergo anomalous changes in the range of small thicknesses of the hard magnetic layer. In the same range of thicknesses, a magnetic aftereffect is found to manifest itself, which is unusual for this type of magnetic structures. The observed features are associated primarily with the kinetics of formation of a crystal structure of the high-coercive layer.

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1. INTRODUCTION

Interest in multilayer magnetic structures that contain magnetic layers and an intermediate nonmagnetic layer is caused by their practical use in spintronic devices. Controlling layers in such devices are the magnetic layers that are made of magnetic materials with different coercive forces. Physical properties of such structures in many respects depend on the state of high-coercive layer. Up to now, magnetic properties of multilayer films in the region of nanothicknesses and, specifically, the effect of high-coercive layer on them are poorly understood. This problem seems to be topical from the fundamental and practical viewpoints, and its solution will provide prediction and formation of magnetic multilayer systems with specified properties.

In this paper, we report the investigation of an unusual magnetic aftereffect in trilayer magnetic films with a thin high-coercive layer.

2. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

The samples under study were the trilayer films prepared by chemical deposition. The first magnetic isotropic high-coercive layer is made of the Co–P compound in the polycrystalline state [1] deposited on a glass substrate from the solution.

The upper low-coercive layer consisted of the amorphous Co–P compound. It was deposited in a constant magnetic field, which led to the appearance of the easy magnetization axis parallel to the field [2].

The intermediate layer was an amorphous nonmagnetic alloy of Ni and P, which was achieved by the corresponding phosphorus content [3].

We studied the samples of two types. In the first-type samples, we fixed the thicknesses of the low-coercive d_2 and nonmagnetic d_3 layers, while the thickness of a high-coercive layer d_1 was varied in the range of 1–25 nm. In the second-type samples, we fixed the thicknesses of the high-coercive and intermediate layers, while the thickness of the low-coercive layer was varied in the range of 0.5–120 nm. Preparation of samples without the intermediate layer with an abrupt transition boundary between the layers is complicated in this technology. This is caused by that at the initial stage of deposition, because of the epitaxial character of the film growth, the first layers will copy the structure of the sublayer.

The chemical composition of the films and their thickness were monitored using the photocalorimetric and X-ray spectral analyses.

The hysteresis loops were measured using the meridional and polar Kerr effects with the frequency of the change of the magnetic field of 0.01 Hz and by the induction method with the frequency of 50 Hz. The dynamic changes of hysteresis loops were recorded on the oscilloscope screen with a WEB camera and written into a videofile. The structural investigations of the film surface were performed using an atomic force microscope.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The films were preliminarily saturated in a constant magnetic field exceeding the coercive force of the

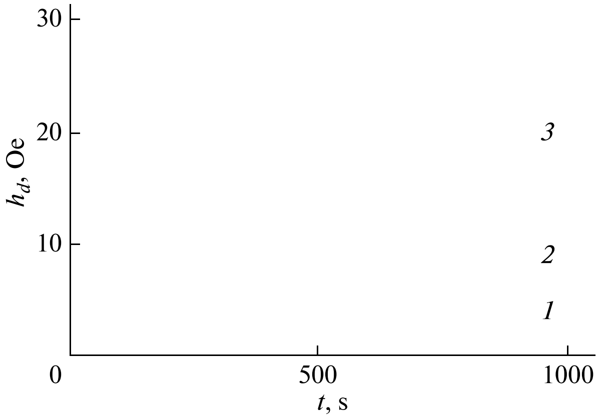

Fig. 1. Dependences of the bias field of the low-coercive layer on the magnetization reversal time for different thicknesses of the high-coercive layer: (*1*) 4, (*2*) 10, and (*3*) 15 nm.

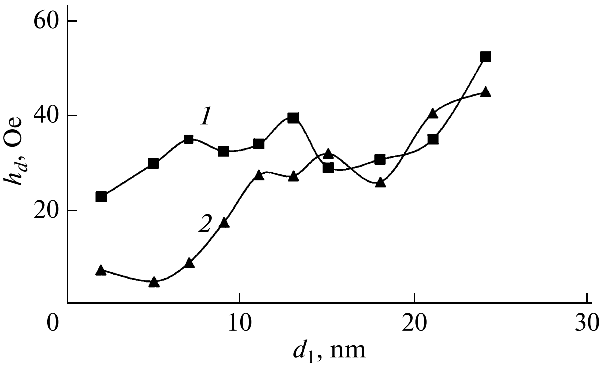

Fig. 2. Dependences of the bias field on the thickness of the high-coercive layer for (*1*) magneto-optical and (*2*) induction measurement techniques.

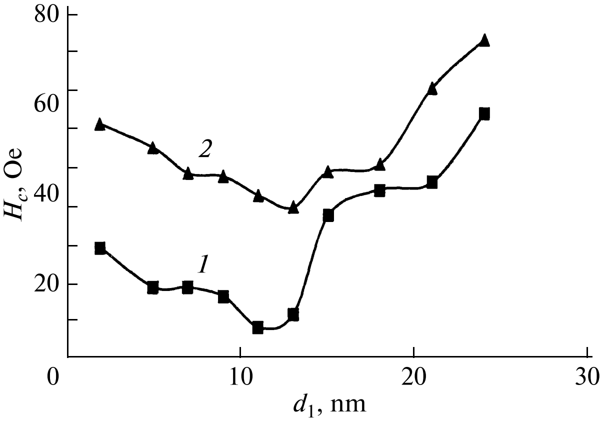

Fig. 3. Dependences of the coercive force of the low-coercive layer on the thickness of the high-coercive layer for (*1*) magneto-optical and (*2*) induction measurement techniques.

high-coercive layer and directed along the easy magnetization axis of the low-coercive layer. After this magnetization, hysteresis loops of the low-coercive layer shifted by quantity h_d with respect to the zero value of the external magnetic field in the direction opposite to the magnetization direction of the high-coercive layer (in the positive direction). Upon the magnetization reversal of the film, the value of h_d decreased with time, and after a lapse of time, the hysteresis loops acquired a shape inherent in the single-layer film. These changes in h_d depend on the amplitude of the magnetization reversal field h: with an increase in h_d, the rate of change in h_d increases. If the amplitude of the magnetic field is selected so that it would somewhat exceed the coercive force of the low-coercive layer, we can establish that the variation of h_d with time depends on the thickness of the high-coercive layer. The time of change in h_d with increasing thickness of the hard magnetic layer increases as shown in Fig. 1.

Figure 2 shows the plot of the dependence of the bias field on the thickness of the hard magnetic layer at the magnetization reversal frequencies 0.01 Hz (measured using the meridional Kerr effect) and 50 Hz (measured by the induction method). The largest differences in the values of h_d determined by these methods are observed when the thicknesses of the hard magnetic layer are less than 10 nm. No differences in the values of h_d measured by these methods are observed in the range of larger thicknesses.

It was established previously [4] that the variation in the thickness of the high-coercive layer exerts a substantial effect on the value of the coercive force H_c of the low-coercive layer. As the thickness increases to ~10 nm, H_c decreases, reaches the minimum value, and increases with a further increase in d_1. These changes in the coercive force especially clearly manifest themselves when increasing frequency of the magnetic field, which leads to the largest differences in the values of the coercive force measured using the magneto-optical and induction methods when the thickness of the hard magnetic layer is less than 10 nm (Fig. 3).

According to Néel [5], the magnetic aftereffect during the quasi-static magnetization reversal can be caused by two physical mechanisms, namely, by the diffusion of the particles and thermal spin fluctuations. Despite the apparent similarity, these phenomena have fundamental distinctions. During the diffusion aftereffect, instant directions of the magnetic moment are stabilized by the diffusion of particles, and as the rate of varying the magnetic field decreases, the coercive force should increase. With the fluctuation mechanism, as the rate of varying the magnetic field decreases, the coercive force decreases since the spin fluctuations induce an additional internal magnetic field.

The observed changes in the coercive force upon varying the frequency of the magnetization reversal field indicate that the magnetic aftereffect in the structures under study is caused by fluctuation processes. This can be additionally evidenced by the characteristic features of the hysteresis loop, which manifest themselves when the amplitudes of the magnetic field somewhat exceed the coercive force of the soft magnetic layer. If the hard magnetic layer of the film is preliminarily saturated in a certain direction coinciding with the easy magnetization axis of the low-coercive layer and it is conventionally accepted that the magnetization of the high-coercive layer is directed to the left, then with the subsequent magnetization reversal, the right back (the ascending branch) of the loop will undergo the dynamic changes. The shape of the back and its location undergo random oscillations near the positions of the quasi-stable equilibrium. As a result of such oscillations, the starting magnetic state of the film turns out to be unstable, and with the further magnetization reversal, the hysteresis loop shifts from the initial location. Such effect was previously observed for the single-layer films and was associated with thermal fluctuations of the internal magnetic field appearing as a result of temperature oscillations of spin moments around the average direction. These fluctuations induce additional magnetic fields that allow the domain boundaries to overcome the potential barriers preventing their motion.

The feature of the observed magnetic aftereffect is in the fact that this effect manifests itself upon magnetization reversal of the soft magnetic layer while it is caused by the fluctuation processes taking place in the high-coercive layer.

In the simplest case, the energy of interaction between the magnetic layers in the trilayer structure per unit area can be expressed in the form [6]

$$\begin{aligned} E &= -m_1 h_1 d_1 \cos(\theta_1 - \theta_2) \\ &= -m_2 h_2 d_2 \cos(\theta_1 - \theta_2), \end{aligned} \quad (1)$$

where m_1 and m_2 are the magnetizations; d_1 and d_2 are the thicknesses of the hard magnetic and soft magnetic layers; θ_1 and θ_2 are the angles between the external magnetic field and magnetizations of the high-coercive and low-coercive layers, respectively; h_1 equals to the effective field acting on the hard magnetic layer from the side of the soft magnetic one; and h_2 is the effective field acting on the soft magnetic layer from the side of the hard magnetic one.

As was established in [7], the low-thick polycrystalline films of the Co–P compound prepared by the chemical deposition represent a nonuniform medium consisting of separate segments or crystal nuclei. Upon applying the magnetic field with a value higher than the coercive force of the hard magnetic layer, the magnetic moments of all such segments are oriented along the direction of this field. Since the sizes of nuclei decrease and magnetic interaction between them weakens as the layer thickness decreases, the uniform magnetized state is unstable and can be violated by an irreversible turn of the magnetization of separate crystallites under the effect of thermal fluctuations. In the trilayer system, such processes in the hard magnetic layer will be stimulated by the effective magnetic field h_1. According to Eq. (1), the magnitude of this field depends on the state of the low-coercive layer, which can lead to a decrease in the activation energy of thermal fluctuations [8]. This mechanism explains the fact that the thermal fluctuations in the single-layer polycrystalline Co–P film do not lead to its spontaneous demagnetization.

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