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Magnetic and Magnetooptical Properties of Nanothick Polycrystalline Co–P Films

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Abstract—Features of the formation of chemically deposited polycrystalline Co–P films with nanometer thicknesses are established by magnetic measurements and analysis of film surface morphology. It is found that the specific value of the magnetooptical Faraday effect in Co–P films exceeds that in Co films by a factor of more than two. This is attributed to the magnetic polarization of a Pd underlayer. It is shown the Kerr effect in Co films is negligibly influenced by the embedding of phosphorus.

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INTRODUCTION

Cobalt thin magnetic films with phosphorus admixture attract the attention of researchers due to the variety of physical properties they exhibit in dependence on their cobalt content and microstructure. The improved morphology and corrosion stability of Co–P films allow us to use them as media for magnetic and thermomagnetic recording [1], and for the fabrication of anticorrosive coatings [2].

One of the methods for fabricating Co–P films is chemical deposition. The advantages of this technique are its simplicity, low cost, and the possibility of obtaining films of homogeneous thickness on surfaces of any configuration. Chemical deposition makes it possible to fabricate multilayer films containing Co–P layers with different structural and magnetic characteristics. At present, the most interesting range of film thicknesses for both fundamental research and application is a few nanometers. The Co–P films in this range of thicknesses remain understudied. The aim of this work is to investigate the magnetic and magnetooptical properties of polycrystalline Co–P films with thicknesses of a few nanometers.

EXPERIMENTAL

Samples for investigation were prepared by chemical deposition and had the multilayer structure typical of this method. For better adhesion, thin SnO_2 and Pd layers were deposited onto the substrate's surface prior to the deposition of Co–P. The magnetic layer consisted of polycrystalline hcp Co–P alloy with the average phosphorous content of ~2.5 weight % optimum for obtaining high-coercivity films. The films were isotropic with the magnetization lying in the film plane.

The polar Kerr and Faraday effects were observed using a zero analyzer with double modulation of the polarization plane at room temperature in a magnetic field of 14 kOe. For comparative analysis, single-layer Co films fabricated by ionic plasma sputtering were studied. Hysteresis loops and magnetization of the films were determined with a SQID magnetometer at room temperature in a magnetic field applied in the film plane. The surface morphology was studied by atomic force microscopy.

RESULTS AND DISCUSSION

The angle of rotation of the polar Kerr effect θ_K in Co–P films nonmonotonically depends on the film thickness (Fig. 1). Positive values of θ_K at very low film thicknesses are caused by the glass substrate effect. Up

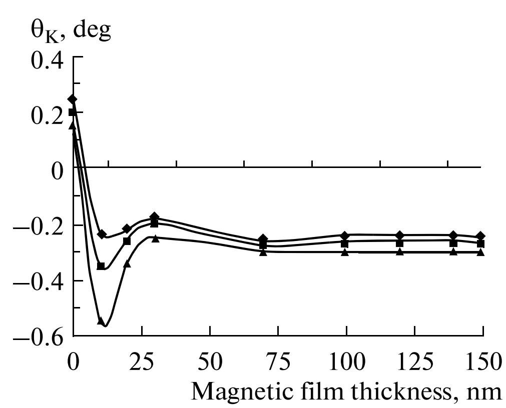

Fig. 1. Dependence of the polar Kerr effect on film thickness for wavelengths of 900 (triangles), 600 (squares), and 400 (diamonds) nm.

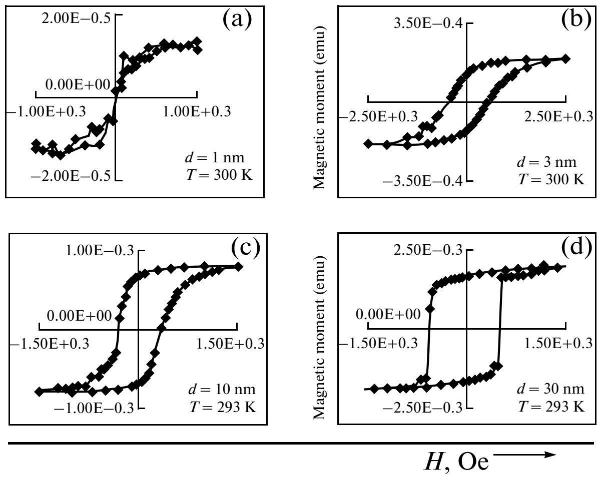

Fig. 2. Hysteresis loops of the meridional Kerr effect of Co–P films.

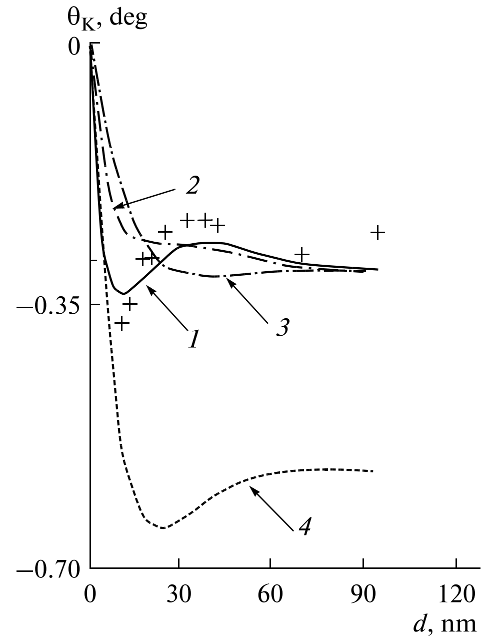

Fig. 3. Calculated dependences of the Kerr effect on the thickness of a magnetic film for different layers.

to thicknesses of ~13 nm, θ_K grows in its absolute value; above this thickness, it drops to a certain constant value. In this range of thicknesses, the Kerr effect depends strongly on wavelength. At great (>30 nm) thicknesses, θ_K depends weakly on both film thickness and wavelength and has a value of around ~–0.2°, coinciding with the value of the Kerr effect we obtained for Co films and consistent with the data reported in [4].

The specific value of the Faraday effect at a wavelength of 500 nm is $\theta_F \sim 4.38 \times 10^5$ deg cm^{-1} for Co–P films and ~2.2×10^5 deg cm^{-1} for Co films; the latter is close to the value of ~2.9×10^5 deg cm^{-1} for bulk cobalt [5].

As was shown in [3], the surface morphology of the films under study is inhomogeneous (granular); the average size of inhomogeneities of the film relief depends on film thickness and nonmonotonically changes with it. In a 4-nm-thick film in particular, the average size of a surface inhomogeneity $\rho \sim 50$ nm; in a 7.5-nm-thick film, $\rho \sim 80$ nm. In a sample with a thickness of 10.5 nm, the value of ρ is about 40 nm. With a further rise in film thickness, the size of inhomogeneities grows again, reaching $\rho \sim 70$ nm at 30 nm. The variation in the shape of the hysteresis loops with film thickness correlates well with the variations in the surface morphology. The hysteresis-free magnetization curve of the film in Fig. 2a indicates that, in the range of low thicknesses, the Co–P films are in the superparamagnetic state and consist of separate noninteracting islands. With a further increase in thickness, the films become more continuous as the islands grow and merge. In this case, the magnetization reversal of the films follows the Stoner–Wohlfahrt scenario with the typical hysteresis loop shown in Fig. 2b. At thicknesses above ~10 nm, a continuous layer is formed and the hysteresis loop becomes almost rectangular (Figs. 2c and 2d).

The variation in magnetization of the films with their thickness could explain the growth of θ_K in the range of low thicknesses (up to ~13 nm), but cannot reduce the Kerr effect with a further increase in thickness. At thicknesses above 13 nm, the magnetization value continues growing while θ_K drops. As was shown in [6], the enhancement of the Kerr effect at low thicknesses could be due to the contribution from the Faraday effect, which is not taken into account in the model of multiple reflections [4]. Our model allows for the reflection of light from the interfaces. The reflectance of the film–substrate system can be written as

$$\tilde{r}^{\pm} = \left|\tilde{r}^{\pm}\right| \exp(i\Delta^{\pm}) = \frac{\tilde{r}_1^{\pm} + \tilde{r}_2^{\pm}\tilde{\beta}^{\pm}}{1 + \tilde{r}_1^{\pm}\tilde{r}_2^{\pm}\tilde{\beta}^{\pm}}, \quad (1)$$

where $\tilde{r}_1^{\pm} = \dfrac{\tilde{n}^{\pm} - 1}{\tilde{n}^{\pm} + 1}$ is the reflectance at the air–film interface, $\tilde{r}_2^{\pm} = \dfrac{b - \tilde{n}^{\pm}}{b + \tilde{n}^{\pm}}$ is the reflectance at the film–substrate interface, b is the refractive index of a substrate, $\tilde{n}^{\pm}$ is the refractive index of a magnetic film for right (+) and left (–) circularly polarized light, $\tilde{\beta}^{\pm} = \exp(-i4\pi\tilde{n}^{\pm} d/\lambda)$, and d is the thickness of a magnetic film. Within this model, the value of the Kerr effect is defined as

$$\theta_K = (\Delta^+ - \Delta^-)/2. \quad (2)$$

If a multilayer system is considered, the calculations are performed in several stages using the effective values of complex optical constants. The optical and magnetooptical parameters for Co reported in the literature [7] were used in our calculations, since there were no data on Co–P. Figure 3 shows the calculated thickness dependences of the polar Kerr effect with regard to multiple reflections in a single-layer film (curve *1*), in the presence of the Pd underlayer (curve *2*), in Co and Pd films (curve *3*), and in Co, Pd, and SnO_2 films (curve *4*) for $\lambda = 600$ nm. It can be seen that step-by-step calculations lead to a change in the shape of the dependence and to the shift of the maximum towards larger thicknesses. Figure 3 also shows the experimental values of $\theta_K(+)$ for Co–P films obtained by chemical deposition. It can be seen that the change in θ_K with thickness can be described by calculated dependence (1) for a single-layer Co film. It should be noted that the variation in θ_K with the thickness of the Co–P films is consistent with the data on the Co films [4] also described by the authors within the model of multiple reflections.

CONCLUSIONS

Based upon the above, we may draw the following conclusions:

(1) The obtained thickness dependence of the polar Kerr effect is determined mainly by multiple reflections in a Co–P layer.

(2) Embedding phosphorous changes the value of the polar Kerr effect in the Co films negligibly.

It follows from the obtained data that the specific value of the Faraday effect in Co–P films exceeds the one in Co films by a factor of two. The enhancement of the Faraday effect in Co–P films is possibly due to the spin polarization of Pd [4]. As is well known, Pd ions exhibit high paramagnetic susceptibility and acquire a ferromagnetic moment in a Co ion environment [8]. Even though such an induced moment is relatively small (~0.48 μ_B [9]), Pd ions have a high orbital moment of localized 4*d* electrons and can therefore contribute to magnetooptical rotation as well.

Final conclusions with regard to this mechanism require additional investigations.

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