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SOLID-STATE ELECTRONICS

Perpendicular Magnetic Anisotropy in Single-Crystal $Co_{50}Pt_{50}$/MgO(100) Films

P. D. Kim*, I. A. Turpanov*, S. V. Stolyar, R. S. Iskhakov*, V. I. Yushkov***, A. Ya. Beten'kova*, L. A. Li*, E. V. Bondareva*, T. N. Isaeva*, and M. M. Karpenko***

** Kirenskiĭ Institute of Physics, Siberian Division, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*
e-mail: kim@iph.krasn.ru
*** Krasnoyarsk State University, Krasnoyarsk, 660041 Russia*
**** Krasnoyarsk State Technical University, Krasnoyarsk, 660074 Russia*

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Abstract—The crystal structure and hysteretic magnetic properties of equiatomic single-crystal CoPt films applied on MgO substrates by magnetron sputtering, as well as modification of these properties by thermal annealing, are studied. Heat-treated films of thickness in the range $2 < d \leq 16$ nm exhibit perpendicular magnetic anisotropy. A correlation between the crystalline anisotropy constant of the CoPt films and the order parameter of the LI_0 superstructure in these alloys is found. The effect of a single-crystalline MgO substrate on the structure and magnetic properties of equiatomic CoPt films is revealed. *© 2004 MAIK "Nauka/Interperiodica".*

Upon ordering of type Al $\longrightarrow$ LI_0, CoPt alloys with a near-equiatomic composition acquire the tetragonal magnetically uniaxial superstructure LI_0. In this crystallogeometrical state, the alloys are characterized by the saturation magnetization $M_s = 800$ G and the crystalline anisotropy field $H_a = 125$ kOe [1]. These values satisfy the condition $H_a \gg 4\pi M_s$, which makes it possible to produce perpendicular magnetic anisotropy in thin films of this equiatomic alloy provided that the films have (001) texture. Therefore, $Co_{50}Pt_{50}$ (like $Fe_{50}Pt_{50}$ and $Fe_{50}Pd_{50}$) alloys are currently viewed as candidates for a high-density planar magnetic data-storage medium.

The magnetic properties of ordered equiatomic CoPt alloys, such as the anisotropy field H_a, the coercive field H_c, and the rectangularity $S = M_r/M_s$ (where M_r is the remanent magnetization) of the hysteresis loop, depend on their microstructure, namely, on the grain size, the density of defects, and the order parameter η of the superstructure LI_0. Upon Al $\longrightarrow$ LI_0 ordering, any of three $\langle 010 \rangle$ axes of the fcc matrix may be taken as the tetragonal axis. Therefore, there exist three types of nuclei C_i (C_1, C_2, and C_3) of the ordered superstructure LI_0 if external actions are absent. As a result, the alloy experiences structural self-organization, causing a complicated microstructure hierarchy [2]. Thus, in fabricating film media with desired magnetic properties, it is necessary to select appropriate methods for forming the microstructure of ordered (or partially ordered) $Co_{50}Pt_{50}$ (as well as $Fe_{50}Pt_{50}$ and $Fe_{50}Pd_{50}$) alloys.

The aim of this work is to study the hysteretic magnetic properties of single-crystal films of equiatomic CoPt alloys applied on single-crystal MgO(100) substrates and reveal the effect of the substrate on the magnetic properties of these ferromagnetic films.

EXPERIMENTAL

The samples used were grown by magnetron sputtering in Ar at a pressure of 2×10^{-4} Torr. In order to avoid chemical inhomogeneity, Co and Pt layers were applied in succession. The application time per metal layer τ_i was taken such that a monomolecular layer of the metal was deposited [3]. The thickness d of the films was varied between 2 and 100 nm and was checked (as well as the chemical composition of the films) by X-ray fluorescence analysis. Isothermal annealing was carried out in a vacuum chamber under a pressure of no higher than 5×10^{-6} Torr.

Hysteresis loops were recorded at room temperature with a vibrational magnetometer at fields $H < 12$ kOe. Measurements were performed in two configurations: $H \parallel n$ and $H \perp n$, where n is the normal to the film surface. The structure of the samples was examined on a DRON-4 diffractometer at room temperature in CuK_α radiation ($\lambda = 0.154$ nm).

STRUCTURE OF THE SAMPLES

Figure 1 shows X-ray diffraction spectra of the films. The diffraction pattern from the as-prepared $Co_{50}Pt_{50}$/MgO(100) structure with $d = 19$ nm (Fig. 1a) indicates that the $Co_{50}Pt_{50}$ alloy with the fcc lattice is initially single-crystalline. Here, only the (200) reflection from the film is detected. The lattice constant of the alloy calculated from the interplanar spacing d_{200} was

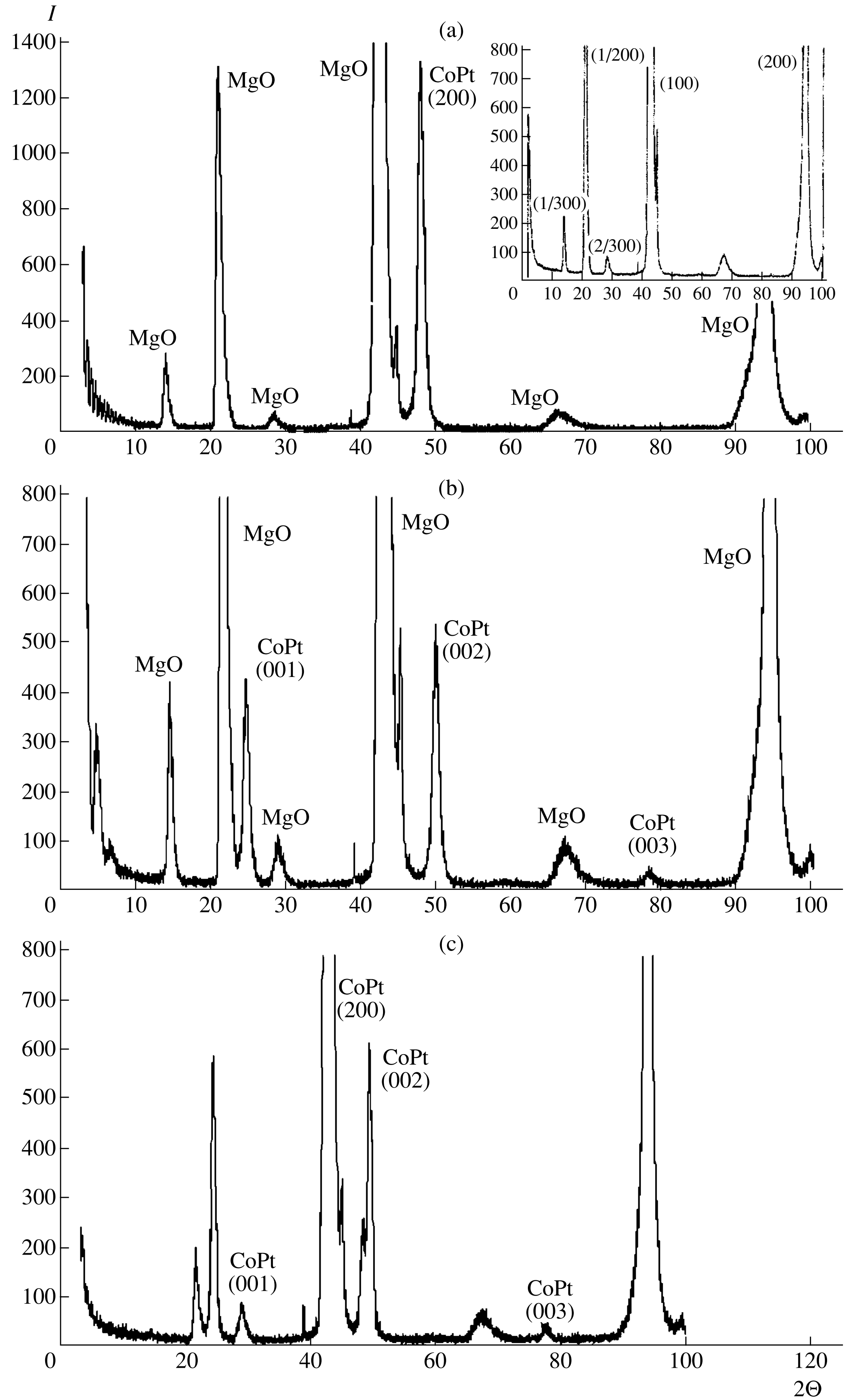

Fig. 1. X-ray diffraction patterns taken from the $Co_{50}Pt_{50}$ films on MgO substrates: (a) as-prepared film with d = 19 nm, (b) heat-treated film with d = 7 nm, and (c) heat-treated film with d = 15 nm. The inset to (a) shows the diffraction pattern from the MgO substrate.

found to be $a = 0.377$ nm. Other peaks in this diffraction pattern are associated with reflections from the MgO substrate. The inset to Fig. 1a shows the spectrum of the substrate. Reflections (1/200), (1/300), (2/300), etc., is likely to indicate that impurity atoms in the MgO are arranged regularly and the MgO substrate has a block structure. Figure 1b demonstrates the diffraction pattern from the 7-nm-thick single-crystal $Co_{50}Pt_{50}$/MgO(100) film annealed at 600°C for 3 h. Reflections (001) and (003) observed suggest that the alloy has the tetragonal superstructure LI_0 after annealing. The tetrad axis runs parallel to the normal n to the film. For the superstructure LI_0 the tetrad axis of which is parallel to the normal, the intensity ratio $I_{(001)}/I_{(002)}$ may be used to estimate the order parameter η [4]. The parameter η turned out to grow with increasing thickness of the $Co_{50}Pt_{50}$/MgO(100) film subjected to annealing. The dependence of η versus the film thickness is presented in Fig. 2. Figure 1c shows the X-ray diffraction pattern taken from the $Co_{50}Pt_{50}$/MgO(100) film with $d = 15$ nm. Here, the (200) reflection intensity is lower than the intensity of the (002) reflection. For the given sample, the ratio $c/a = 0.978$. The presence of the (200) reflection indicates that the $Co_{50}Pt_{50}$/MgO(100) film under study has such regions of the superstructure LI_0 where the tetrad axis lies in the plane of the film. In fact, as the film becomes thicker than 150 nm with the annealing conditions remaining the same, the (200) reflection intensity grows. This means that the fraction of LI_0 regions with the tetrad axis lying in the plane of the film increases.

MAGNETIC PROPERTIES OF THE FILMS

In the as-prepared state, the CoPt films had two easy magnetic axes, lying in the plane of the film orthogonally to each other. The rectangularity S of the hysteresis loop for the as-prepared films was 0.6–0.8 throughout the range $2 < d < 100$ nm. The coercive field for these films, about 500 Oe, also did not depend on the thickness d. Heat treatment of the as-prepared films at $T = 600$°C for 3 h radically changes the hysteretic magnetic properties. For the films with $d \leq 16$ nm, such a heat treatment produces an easy magnetic axis that is aligned with the normal to the film. For $d > 16$ nm, the easy magnetic axis lay in the plane of the film as before. The hysteresis loop rectangularity measured in the easy direction was found to be 0.9–1.0. Figure 3 shows the normalized dependences $M(H)$ ($H \parallel n$, $H \perp n$) for the annealed film with $d = 10$ nm. The dependences imply the presence of perpendicular magnetic anisotropy. Isothermal annealing is seen to make the film magnetically hard. The coercive field H_c for the films thicker than 16 nm varied between 6 and 10 kOe. For the annealed films with $d < 16$ nm, the value of H_c depends the film thickness: $H_c = H_c(d)$. The experimental dependence $H_c(d)$ for these films, which are characterized by $S = 1$, is given in Fig. 4.

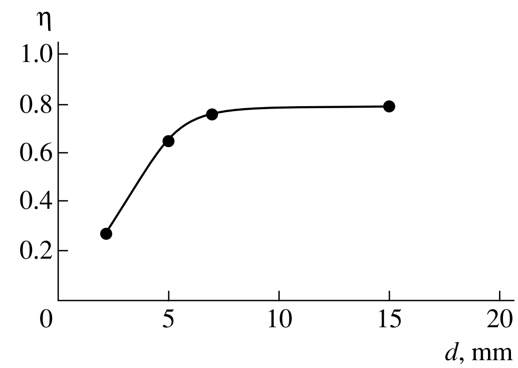

Fig. 2. Order parameter η of the heat-treated $Co_{50}Pt_{50}$/MgO films vs. d.

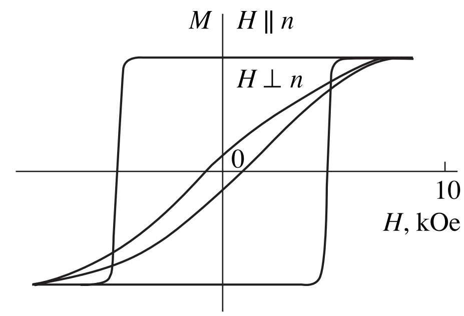

Fig. 3. Normalized dependences $M(H)$ obtained in two configurations ($H \parallel n$, $H \perp n$) for the heat-treated $Co_{50}Pt_{50}$/MgO film with $d = 10$ nm.

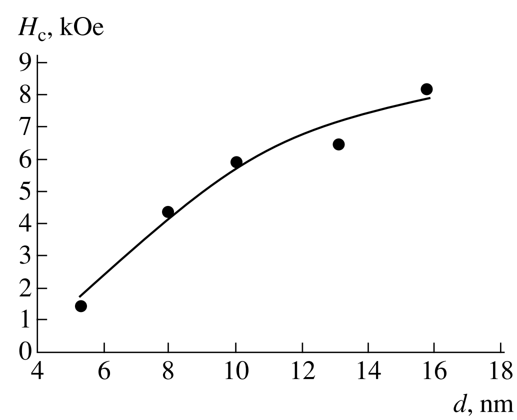

Fig. 4. Coercive field $H_c(d)$ vs. thickness d measured in the easy magnetic direction for heat-treated $Co_{50}Pt_{50}$/MgO films.

The coercive field H_c for single-crystal heat-treated $Co_{50}Pt_{50}$/MgO(100) films with $d < 16$ nm and $S = 1$ is measured as the difference between the crystalline anisotropy field H_a and the demagnetizing field of the film: $H_c = H_a - 4\pi M$ [5]. Therefore, our experimental dependence $H_c(d)$ may be used to calculate H_a and, hence, the crystalline anisotropy constant $K = H_aM/2$ ($M = 800$ G), a fundamental parameter of a ferromagnet. In this way, for single-crystal ordered (or partially ordered) 2- to 16-nm-thick $Co_{50}Pt_{50}$/MgO(100) films with the structure LI_0, which exhibit perpendicular magnetic anisotropy, we found that the constant K varies in the interval 4×10^6–8×10^6 erg/cm^3.

RESULTS AND DISCUSSION

Heat treatment of disordered thin films of the $Co_{50}Pt_{50}$ solid solution on single-crystal MgO(100) substrates produces the ordered superstructure LI_0. Analysis of the hysteretic magnetic properties of these alloys shows that (i) the heat-treated films with thicknesses $d \le 16$ nm exhibit perpendicular magnetic anisotropy and (ii) the coercive field H_c measured along the easy magnetic axis depends on the film thickness (Fig. 4).

It is known that a film of an alloy differs in properties from its bulk state. First, thin films have an elevated concentration of defects. Second, a film is essentially a 2D object. Third, the state of the film is greatly influenced by the substrate.

Perpendicular anisotropy discovered in $Co_{50}Pt_{50}$/MgO(100) thin films with $d \le 16$ nm results from lattice match between the ferromagnetic alloy and substrate. The tetrad axis along ⟨100⟩ and ⟨010⟩ directions is difficult to form because of a rise in the elastic strain energy in the thin ferromagnetic film. The fact that only one ⟨001⟩-directed nucleus of the ordered structure LI_0 (Fig. 1b) originates is a consequence of self-organization, which minimizes the elastic strain energy. As the $Co_{50}Pt_{50}$ film gets thicker, the effect of the single-crystal MgO substrate weakens; therefore, all three types of ordered domains C_i (C_1, C_2, C_3) (Fig. 1c) may arise in thick annealed films. Accordingly, the easy magnetic axis becomes parallel to the plane of the magnetic film and isotropic over its plane.

Let us now discuss the dependence $H_c(d)$ (Fig. 4). The increase in the coercive field with the thickness of the $Co_{50}Pt_{50}$ ferromagnetic film means the growth of the crystalline anisotropy constant K. In our opinion, such a behavior reflects the variation of the order parameter η in the ordered superstructure LI_0 (Fig. 3). In fact, in the films with this superstructure, the dependences $H_c(d)$ (Fig. 4) and $\eta(d)$ (Fig. 2) found experimentally correlate when the thickness varies between 2 and 16 nm. As η of the CoPt alloy increases, so does H_c (and hence K). We suppose that the dependence of η on the thickness of the film with partially ordered superstructure LI_0 also follows from a high lattice match between the ferromagnetic single-crystal $Co_{50}Pt_{50}$ film and single-crystal MgO(100) substrate. Our reasoning is as follows. In the case of the fcc $\longrightarrow$ LI_0 phase transition, the volume of the alloy must remain unchanged: $V_{fcc} \longrightarrow V_{LI_0}$ or $a^3 = a'^2c$, where a' and c are the parameters of the tetragonal lattice of the LI_0 phase. Upon ordering, c decreases. For the completely ordered superstructure LI_0 (η = 1), c/a = 0.972 [2]. Consequently, a' in such films is bound to increase. However, in the thin single-crystal films studied, a' cannot change because of a film–substrate lattice match; in other words, the substrate in thin-film single-crystal $Co_{50}Pt_{50}$/MgO(100) structures prevents ordering in the range of small d mentioned above. As the $Co_{50}Pt_{50}$ film thickens, the effect of the MgO(100) substrate weakens, since the elastic strain drops as $1/d$ and the order parameter η of the alloy grows.

Thus, we investigated the hysteretic magnetic properties of single-crystal $Co_{50}Pt_{50}$ films on MgO(100) substrates. In ordered 2- to-16-nm-thick films with the LI_0 superstructure, the presence and degree of perpendicular magnetic anisotropy are shown to be totally controlled by the single-crystal MgO structure. The substrate influences the formation of the crystal lattice of the ordered ferromagnetic alloy twofold: it (i) favors the appearance of the tetrad axis in the alloy along the normal to the film and (ii) prevents ordering in the alloy.

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