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MATERIALS SCIENCE ASPECTS OF FePt-BASED THIN FILMS' FORMATION

The goal of this review is consideration of basic physical and materials science approaches for providing predefined properties of nanosize thin FePt-based films. Achievement of such properties is required for the industrial application of these materials as magnetic ultrahigh-density recording media. Various approaches are considered to solve the problems such as the reduction of the ordering temperature, formation of the requisite crystallographic orientation of the ordered-phase grains, increase of the coercivity, and providing of the possibility to control the change in the magnetization of these materials.

Keywords: ordered $L1_0$-FePt phase, phase transformations, thin films, magnetic recording.

Introduction

The rapid development of information-communication technologies causes a necessity of a permanent increase in the storage devices capacity. Consequently, there is a rise of the demand to create new ferromagnetic materials with exceptional magnetic properties.

Ferromagnetic thin films used for magnetic data storage applications have to satisfy the following basic requirements: providing a high signal-to-noise ratio and thermal stability with increasing data storage density as well as the possibility of changing the material magnetization using existing magnetic heads.

At magnetic recording, one bit of stored data corresponds to a material area consisting of one or several ferromagnetic grains. Thus, increasing of the recording density requires reducing the size of grains,

which are used to record a single bit of data. However, a decrease in the grain size of the recording layer leads to a decrease in the energy barrier of magnetization reversal. At very small dimensions of ferromagnetic grains, a superparamagnetic effect could be observed as the phenomenon of magnetic domains magnetization reversal under the influence of atoms thermal fluctuations without an external magnetic field. To provide the thermal and temporal stability of the recorded data, the above-mentioned energy barrier must significantly exceed the thermal energy:

$$E = K_u V \geq (50-70) k_B T,$$

where K_u is a constant of magnetocrystalline anisotropy, V is a volume of a ferromagnetic grain, k_B is the Boltzmann constant, and T is a temperature.

The phenomenon of superparamagnetism is a crucial obstacle for further increasing the magnetic recording density by reducing grains size of the recording layer. Application as a recording layer of hard magnetic materials with a high energy of magnetocrystalline anisotropy could be the solution of this problem. This approach allows using materials with a smaller grain size as a recording medium, keeping the thermal stability of the media. The magnetic characteristics and calculated sizes of the minimal thermal stable grains of the known materials with a high magnetic anisotropy are listed in Table 1 [1].

As could be seen from Table 1, the highest energy of magnetocrystalline anisotropy corresponds to $SmCo_5$ alloy. Thermally stable 2.7–2.2 nm grains could be obtained using this material. However, this alloy contains a rare earth metal Sm, significantly reducing its corrosion resistance and, therefore, making it unsuitable for application as a durable storage medium. Another prospective material for improving mag-

Table 1. **Physical properties of different materials with a high magnetic anisotropy [1]**

Type	Material	Magnetocrystalline anisotropy energy K_u, 10^7 erg/cm³	Saturation magnetization M_s, emu/cm³	Coercivity H_c, kOe	Curie temperature T_c, °C	Grain diameter D_p, nm
Co-based	CoCrPt	0.2	298	13.7	–	10.4
	Co	0.45	1400	6.4	1120	8.0
	Co_3Pt	2.0	1100	35	–	4.8
$L1_0$	FePd	1.8	1100	33	490	5.0
	FePt	**6.6–10**	**1140**	**116**	**480**	**3.3–2.8**
	CoPt	4.9	800	123	570	3.6
	MnAl	1.7	560	69	377	5.1
Rare-earth transition metals	$Fe_{14}Nd_2B$	4.6	1270	73	312	3.7
	$SmCo_5$	11–20	910	240–400	727	2.7–2.2

netic recording density is FePt alloy with an ordered $L1_0$-type (super) structure. The value of magnetocrystalline anisotropy energy of $L1_0$-FePt phase is in the range of $(6.6-10) \cdot 10^7$ erg/cm³, and calculated minimal thermally stable grain size is 2.8 nm [1]. Calculated maximal possible recording density of thin films based on $L1_0$-FePt phase is 3–5 TB/inch² [2]. However, application of these materials requires solving of some physical and materials science problems, which will be considered further.

Crystal Structure Peculiarities of the Fe–Pt-Based Materials

The ordered magnetically anisotropic $L1_0$-FePt phase has a face-centred tetragonal (f.c.t.) crystal structure, which is formed by a decrease in lattice parameter of a disordered $A1$-FePt face-centred cubic (f.c.c.) phase along one crystallographic axis (c) and increase in the lattice parameters along two other axes (a). Such changes in the crystal structure are caused by the rearrangement of Pt and Fe atoms with the formation of a regular alternation of the atomic planes of these elements.

The disordered $A1$-FePt phase forms in FePt thin films structure after deposition onto substrates at temperature below 400 °C. Since the melting point of the equiatomic FePt alloy is approximately 1560 °C, the rate of diffusion processes *via* the bulk mechanism at temperatures below 400 °C is extremely low [3]. It means that, for the diffusion formation of the ordered $L1_0$-FePt phase from the initially disordered $A1$-FePt solid solution, a high-temperature treatment or deposition of thin films onto heated substrates are required. However, the heat treatment is accompanied by recrystallization processes, which rate increases rapidly with a temperature rise. This fact causes the main materials science problem, which has to be solved for the application of FePt based films as a magnetic ultrahigh-density recording medium, namely, ordering temperature reduction.

In addition, in order to increase a data storage density, the orientation of the easy magnetization axis perpendicular to the film plane is required. However, the deposition of the FePt based films is accompanied by growth of the disordered $A1$-FePt phase grains in the [111] direction, which is explained by the lowest value of the (111) plane surface energy comparing with other crystallographic planes. Such feature causes the following materials science obstacle in the FePt-based data carriers development: the formation of a preferred orientation of the $L1_0$-FePt phase grains along the [001] crystallographic direction. It is also importantly to ensure a magnetic insulation of the neighbouring ferromagnetic grains in order to control their magnetic properties. A small size of grains and their narrow size distribution, as well as obtaining a flat thin film surface are also required.

Optimal Concentration Ratio of Fe and Pt in the Ordered Phase

Since the ordered $L1_0$-FePt phase is not a stoichiometric compound but has a certain homogeneity region (40−55 at.% Pt), the question on optimal composition providing desired physical properties of thin films arises. For instance, Ref. [4] reports that the maximal ordering degree of the 0.5 μm thick FePt films can be reached for the films with the Pt concentration in the range of 47−50 at.%. In this case, the ratio of the crystal lattice parameters of the ordered phase (c/a) and ordering temperature take their minimal values.

It is necessary to stress that films with Pt content of 47 at.%− 50 at.% have not only much higher ordering degree at lower temperatures as compared to films with a higher or lower Pt content but also they are more ordered (*i.e.*, are characterized by higher long-range order parameter) at higher heat treatment temperatures. Authors attribute this finding to the activation energy of $A1 \rightarrow L1_0$-FePt phase transformation, acquiring its minimal values in the Pt concentration range of 47−50 at.% [5]. Another confirmation that the above-mentioned concentration range is optimal deals with the fact that 0.5 μm thick FePt films obtained by deposition on a substrate at 250 °C have a completely ordered $L1_0$ structure at the Pt concentration of 48.2 at.%. At the same time, in order to obtain a fully ordered structure in films with lower or higher Pt content, the substrate temperature during deposition has to be increased up to 300 °C [9]. Note that the bulk Fe-based crystal structures, where concentration of alloying element is close to equiatomic content, are also characterized by a higher long-range order parameter as compared to those with a lower content of an alloying element [6−8].

However, it was found that the dependence of the magnetocrystalline anisotropy energy constant on the Fe content in the ordered $L1_0$-FePt phase does not obey the regularity established for the ordering parameter value [10]. The structure and magnetic properties of epitaxial 50 nm thick FePt films obtained by deposition onto heated up to 620 °C single-crystal MgO(001) substrate were studied [10]. It was determined that the calculated value of the magnetocrystalline anisotropy energy of the ordered $L1_0$-FePt phase increases monotonously with an increase in the Fe content from 46 at.% to 52 at.%. In contrast, the value of the ordering parameter reaches the maximum value for equiatomic film.

Thus, it can be concluded that, in order to obtain $L1_0$-FePt films with the maximum value of the magnetocrystalline anisotropy, it is favourable to use films with a deviation of components concentration from the equiatomic one to a slight increase of Fe. However, it is known that the ordering degree of the hard magnetic $L1_0$-FePt phase decreases with the grain size reduction [11, 12]. This phenomenon is explained by
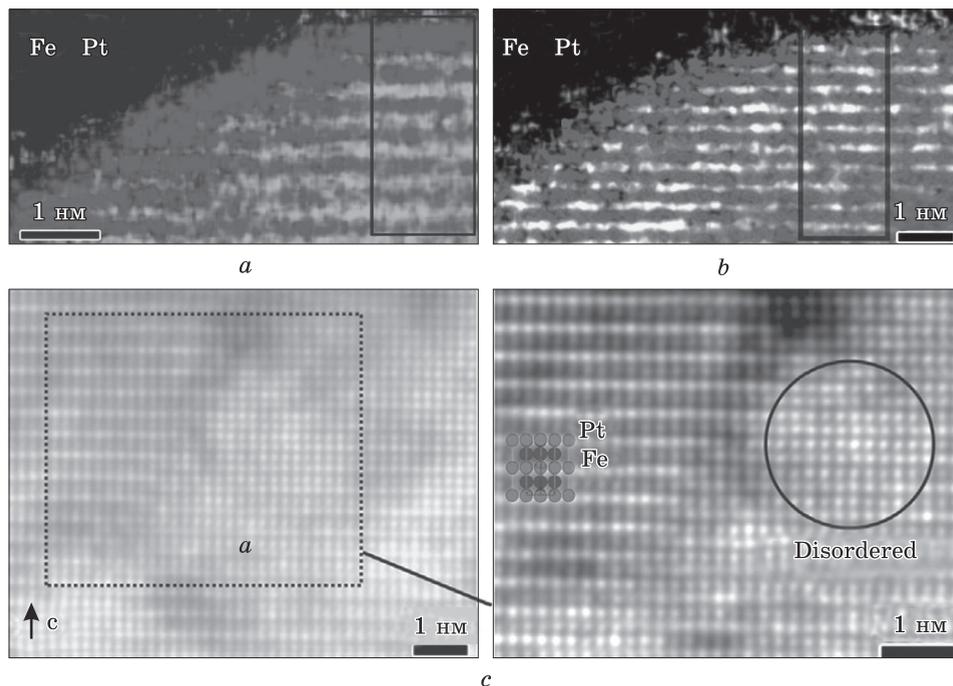
Fig. 1. Concentration maps of Fe and Pt obtained from the surface of FePt grains of $Fe_{51.8}Pt_{48.2}$ (*a*) and $(Fe_{51.8}Pt_{48.2})_{99.4}Ag_{0.6}$ (*b*) films. Transmission electron microscopy images are taken from inside of a FePt grain of film with $Fe_{51.8}Pt_{48.2}$ composition (*c*) [14]

the presence of Pt segregations in the near-boundary regions of FePt grains [13–15], causing some deviation of the concentration in the grain bulk from the equiatomic one, and leading to a decrease in the $L1_0$-FePt phase ordering parameter.

Figure 1 shows concentration distribution maps of Fe and Pt obtained in Ref. [14] by the x-ray energy-dispersive spectroscopy. Pt segregations in the regions close to the grain boundaries of the ordered $L1_0$-FePt phase can be clearly seen. There is a decrease in the coercivity of films with a higher iron content ($Fe_{51.8}Pt_{48.2}$) compared with the films with a higher Pt content. This could be explained by the presence of the disordered regions in the $L1_0$-FePt grains (Fig. 1, *c*). It was also found that a doping with silver prevents the formation of Pt segregations in the near-boundary regions of nanoscale grains in $(Fe_{51.8}Pt_{48.2})_{99.4}Ag_{0.6}$ films (Fig. 1, *b*). In addition, it was established from the first principle calculations that the formation of Pt surface segregations is more pronounced at the FePt grain size less than 15 nm [14].

Thus, the maximum value of the magnetocrystalline anisotropy energy (which is required for the application of these materials as a magnetic recording medium) is attributable for FePt films with a slightly

higher Fe content (≈52 at.%). However, when the grain size is reduced down to 15 nm, in order to eliminate the effect of Pt segregation on the grains surface, it is reasonably to use films with a higher Pt content.

Methods of Ordered Phase Formation Temperature Reduction

Stress-State Control in Thin FePt-Based Films

It has been shown in many studies that the deposition of Fe and Pt separate metal layers instead of the disordered FePt alloy is an effective method of the ordering temperature reduction during post-annealing process [16, 17]. For instance, an influence of additional stresses arising at the interface between metal layers on the rate of ordering in FePt thin films was studied in Ref. [16]. FePt (72.8 nm) thin films, [Fe(3.6 nm)/Pt(3.6 nm)]$_{10}$, [Fe(5.2 nm)/Pt(5.2 nm)]$_7$ and [Fe(7.3 nm)/ Pt (7.3 nm)]$_5$ multilayers were obtained by magnetron sputtering onto the glass substrates at room temperature and then heat treated at 300– 550 °C for 30 minutes. Ordering process was studied by magnetic properties measurements. Even after annealing at 350 °C, the coercivity of [Fe (5.2 nm)/Pt (5.2 nm)]$_7$ films was about 160 kA/m, while coercivity of the single-layer film did not exceed 50 kA/m. Figure 2, *a* demonstrates that the coercivity of both films increases with the rise of annealing temperature. However, multilayer films have much more pronounced hard magnetic properties in comparison to FePt thin film, indicating their much higher ordering degree. The authors of Ref. [16] also showed that decrease in the thickness of separate Fe and Pt layers contributes to the acceleration of the ordering due to reduced diffusion paths of both Fe and Pt atoms.

The beneficial effect of an increase in the number of interfaces between the Fe and Pt layers on the ordering temperature reduction was
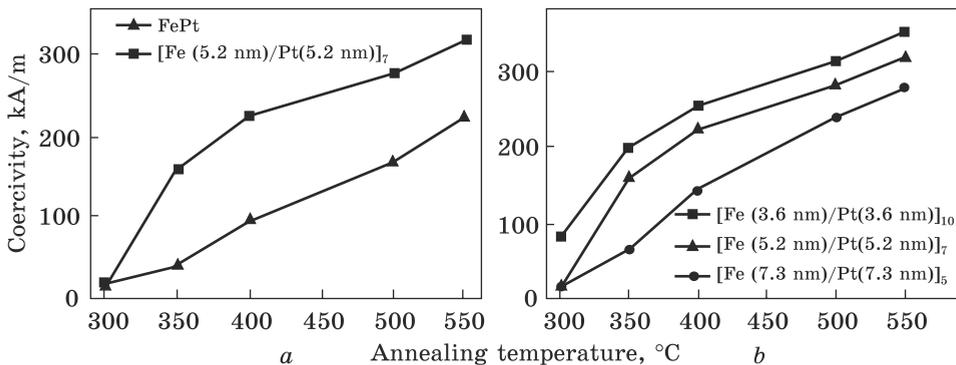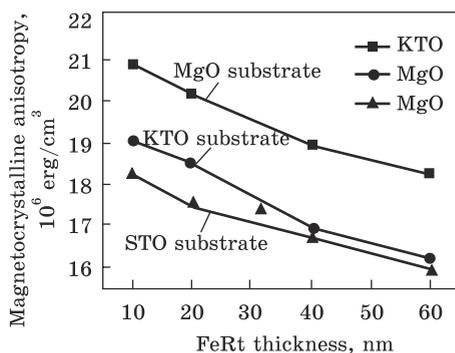
Fig. 2. Temperature dependence of coercivity of FePt(72.8 nm) and [Fe (5.2 nm)/ Pt(5.2 nm)]$_7$ films (*a*) as well as for multilayer Fe/Pt stacks with various thicknesses of the layers (*b*) [16]

Fig. 3. Dependence of the magnetocrystalline anisotropy of $L1_0$-FePt films deposited onto different substrates on the film thickness [19]

observed in Ref. [18]. The Pt(15 nm)/Fe(15 nm) and [Pt(7.5 nm)/Fe(7.5 nm)]$_2$ layered stacks were obtained by magnetron sputtering onto thermally oxidized single crystal Si(001) substrates and annealed in the range of 300–900 °C for 30 s. It was found that the ordering temperature decreases by 100 °C in the [Pt(7.5 nm)/Fe(7.5 nm)]$_2$ multilayers, comparing with the bilayer films, where the ordering begins at 700 °C. In addition, according to the results of x-ray diffraction (XRD) analysis, four-layer compositions have a higher ordering degree as compared to the bilayer films at the same treatment temperatures.

The mechanical stresses, caused by the mismatch between crystal structure parameters of the substrate and the metal layer, affect the ordering rate as well as the structural and magnetic properties of thin films [19, 20]. For instance, mismatch between the lattice parameters, calculated in Ref. [19], were 8.63%, 3.44%, and 1.44% for FePt(10 nm) films deposited onto MgO(001), KTaO$_3$(001), and SrTiO$_3$(001) substrates, respectively. It was revealed that thin films deposited onto the MgO(001) substrate at 380 °C have a higher value of magnetocrystalline anisotropy (Fig. 3) as compared to the films deposited onto other single-crystal substrates under the same conditions. This effect is explained by the higher level of tensile stresses at the film/substrate interface in the case of MgO. In addition, it was revealed that an increase in the film thickness leads to a loss in the magnetocrystalline anisotropy, which is caused by stress relaxation in the film.

Thus, the results of numerous studies suggest as follows. An increase in the level of initial stresses in films and increase in the number of interfaces between the layers as well as an increase in the mismatch between the crystal structure parameters of the film and the substrate could significantly contribute to the acceleration of diffusion and, consequently, to the ordering temperature reduction.

Alloying of FePt Films

An effective method to reduce the $A1 \rightarrow L1_0$-FePt phase transformation temperature is the alloying of FePt based thin films with additional elements. We can conventionally distinct alloying elements in these films

into two groups: (1) elements forming ternary compounds with FePt; (2) elements acting as segregated ones along the grain boundaries of the ordered phase.

During the heat treatment of thin FePt-based films alloyed with such elements and compounds as Au, Ag, C, TiO_2, SiO_2, these elements segregate from the disordered $A1$-FePt-phase with the formation of additional crystal structure defects. The formation of additional defects promotes the acceleration of the ordered $L1_0$-FePt phase formation. In addition, the segregation of these nonmagnetic elements along the grain boundaries of the ordered phase leads to a decrease of the exchange interaction between neighbouring ferromagnetic grains, enhancing films coercivity.

Many studies have found a positive effect of the alloying by Ag on the decrease of the ordering temperature in FePt films [21, 22]. This influence could be explained by the insolubility of Ag in FePt. During heat treatment, Ag segregates from the disordered FePt phase, generating additional vacancies, which in turn contributes to the diffusion acceleration. However, Ref. [23] reports that Ag can have a limited solubility in the ordered $L1_0$-FePt phase, where Ag concentration can reach 5.9 at.%. In this case, Ag substitutes the Fe positions in the lattice of the ordered phase.

In Ref. [21], it was found that, in the $[Fe_{49}Pt_{51}]_{88}Ag_{12}$ nanoparticles (3.5 nm) obtained by the chemical synthesis, the ordering temperature is lower by $\approx 100-150$ °C in comparison to the particles without Ag. The coercivity of $[Fe_{49}Pt_{51}]_{88}Ag_{12}$ particles annealed for 30 minutes at 400 °C was 3.4 kOe. At the same time, after heat treatment under the similar conditions, the FePt particles were superparamagnetic. The FePt nanoparticles (4 nm) with Ag content of 20 wt.% were obtained by chemical synthesis in Ref. [22]. Authors [22] found that the activation energy of the ordering is lower (by 32 kJ/mol) in comparison to the FePt particles without Ag. This decrease in the activation energy is attributed to the rise in the vacancy concentration in $3 \cdot 10^3$ times and corresponding increase in the diffusion coefficients of Fe and Pt. The increase in the number of vacancies is caused by the diffusion of Ag atoms from the FePt matrix during the heat treatment. The appearance of additional vacancies is the reason of the ordering temperature decrease in the alloyed FePt nanoparticles by approximately 250 °C.

The same arguments could be applied to explain the acceleration of the ordering observed in the FePt based films alloyed with other elements having no or having limited solubility in the ordered phase.

The similar effect on the reduction of the ordering activation energy in FePt based films occurs when Sn is introduced as an alloying element [24]. The 25 nm thick FePtSn films with a Sn content of 0.8–5.8 at.% annealed for one hour at 300 °C have hard magnetic properties (H_c = 5 kOe). At the same time, the structure of FePt films without Sn

is completely disordered. An increase of the lattice parameter of cubic phase was observed in as-deposited FePtSn films. This effect was explained by the presence of internal stresses caused by the lattice over-saturation by Sn. When the annealing temperature is raised up to 600 °C, the lattice parameters take values typical for the ordered $L1_0$-FePt phase. This change indicates a decrease of the Sn solubility in the ordered phase as compared to the disordered one. Authors claim that the presence of internal stresses after the films deposition as well as the generation of additional defects during Sn segregation from the over-saturated FePtSn solid solution during annealing, result in a reduction of the ordered $L1_0$-FePt phase formation temperature.

The following group of alloying elements, considered for reduction of the formation temperature of the $L1_0$-FePt phase, cover elements forming ternary compounds with FePt. Typically, such compounds have a lower melting point than the $L1_0$-FePt phase. Typical elements from this group are Cu, Mn, and Ni.

The introduction of Cu in FePt films promotes the reduction of the formation temperature of the hard magnetic ordered phase by forming a ternary $L1_0$-FePtCu compound [25–27], where Cu atoms substitute Fe positions [28]. For example, authors of Ref. [27] studied the effect of alloying by Cu of the FePt films (50 nm) obtained by magnetron sputtering onto SiO_2/Si(001) substrates at room temperature and post-annealed in a wide temperature range (300–700 °C) for 1 hour. It was found that the introduction of 15 at.% Cu promotes a decrease in the ordering temperature to ≈300 °C, while in the films without Cu, this temperature is ≈400 °C.

Authors of work [29] investigated the effect of Ni concentration on the ordering in FePt nanoparticles. The $(Fe_{52}Pt_{48})_{100-x}Ni_x$ particles with an average size of 3 nm were obtained by chemical synthesis. The Ni concentration was varied within the range of 8–21 at.%. The particles were annealed in the temperature range of 400–700 °C. It was found that the ordered $L1_0$-FePt phase was formed after annealing at 500 °C in the FePt particles. However, particles alloying by Ni leads to the increase of the ordering onset up to 600 °C. The XRD results indicate that, with increasing Ni content, the ordering degree of annealed nanoparticles decreases. Investigation of magnetic properties also indicates a decrease of the long-range order in the $L1_0$-FePt phase with a rise of the Ni content: a drop of the coercivity from 7.6 kOe to 5.3 kOe at a Ni concentration of 8 and 17 at.%, respectively, was revealed.

The results presented above show that alloying of thin FePt films with elements forming ordered ternary compounds during heat treatment could promote a reduction of the ordering temperature. Herewith, not all such elements have a positive effect on the phase formation and magnetic properties of FePt based films.

Insertion of Additional Layers into the Thin FePt Films

In order to reduce the ordering temperature and obtain desired properties of FePt-based films, not only the effect of alloying with additional elements but the introduction of additional layers of alloying elements was also widely studied. For instance, a heat treatment of FePt-based stacks with Ag additional layers leads to the diffusion of Ag atoms towards the outer surface of the films. This effect could be explained by a relatively low value of the Ag surface energy [30]. Diffusion of Ag atoms leads to the appearance of additional crystal structure defects, promoting the ordering process. Ag atoms also occupy the grain boundaries and, thereby, suppress grains growth during the heat treatment.

The authors of Ref. [31] obtained the ordered $L1_0$-FePt phase by annealing (at 350 °C for 1 hour) of bilayer FePt (112 nm)/Ag (150 nm) films deposited onto a glass substrate. At the same time, 112 nm thick FePt films without an Ag underlayer have a disordered $A1$-FePt structure after annealing under similar conditions.

The low-temperature phase formation in Fe/Pt bilayers as well as the effect of the intermediate Ag layer introduction were investigated in work [32]. After deposition, the Pt(15 nm)/Fe(15 nm) and Pt(15 nm)/Ag(10 nm)/Fe(15 nm) films were heat-treated in a vacuum in a temperature range of 320−340 °C with various annealing time. According to chemical depth profiling and XRD data, it was found that, after annealing at 340 °C for 4 hours, Fe and Pt are uniformly distributed through the film thickness. Moreover, there is a certain amount of the ordered $L1_0$-FePt phase along with the soft magnetic $A1$-FePt phase in the films structure. It was assumed that the phase formation under these heat treatment conditions occurs *via* formation of a reaction layer induced by grain boundary diffusion [33]. It was determined that the introduction of an additional intermediate Ag layer in this case decelerate the formation of the ordered $L1_0$-FePt phase. The authors explain this effect by the fact that, at the initial stages of heat treatment, Ag diffuses to the film surface and partly dissolves in the Pt, slowing the diffusion interaction between Fe and Pt along the grain boundaries. In contrast, the introduction of an additional intermediate Au layer leads to an acceleration of the low-temperature $L1_0$-FePt phase formation induced by the grain-boundary diffusion [34]. The XRD results indicate the presence of the ordered $L1_0$-FePt phase in the structure of the Pt(15 nm)/Au(10 nm)/Fe(15 nm) layered stacks even after heat treatment at 330 °C for 24 hours. According to the films' chemical depth profiling, an almost complete diffusion intermixing of the Fe and Pt layers occurred in the three-layer stacks after annealing for 62 hours. At the same time, the mutual diffusion of components in the bilayer films develops much less intensively. Formation of the ordered phase in

the bilayer Pt(15 nm)/Fe(15 nm) films after annealing at 330 °C for 62 hours was not revealed according to XRD results.

The reduction of ordering temperature in Ref. [35] was achieved *via* the deposition of a Fe layer (2.67 nm) on a metastable $Pt_{65}Ag_{35}$ (3.61 nm) phase layer with a following heat treatment. Using the transmission electron microscopy and grazing incidence x-ray diffraction analysis, the authors [35] found that the ordered $L1_0$-FePt phase begins to form after annealing at the temperature of 230 °C for 2 hours. This effect can be explained by the Ag diffusion from the metastable PtAg phase, contributing to the formation of excessive vacancies in the AgPt layer and to the following acceleration of the diffusion interaction between Fe and Pt. As a sequence, a decrease in the ordering temperature was observed.

Effect of an additional Bi layer introduction on the temperature of ordered $L1_0$-FePt phase formation was investigated in Ref. [36]. After deposition onto a glass substrate, the FePt(20 nm)/Bi(20 nm) layered stacks were further heat treated in a temperature range of 300–500 °C for 20 minutes. It was revealed that the ordered $L1_0$-FePt phase is formed even at a temperature of 350 °C in bilayer films, which is lower by 50 °C as compared to films without the Bi sublayer. The presence of the Bi layer contributes to a significant increase in the coercivity of the bilayers, showing the value of 13 kOe after annealing at 400 °C. However, in the heat-treated bilayer films, the grain size is almost twice larger in comparison with FePt films annealed under the same conditions. The authors give the following explanation of the obtained results: Bi has a significantly lower value of the surface energy as compared to Fe and Pt, and does not interact with these metals. That is why the Bi atoms diffuse to the film surface by the grain boundary mechanism even at relatively low annealing temperatures. The Bi atoms generate a large number of additional crystal structure defects during diffusion since Bi has a larger atomic radius comparing with Fe and Pt. An increase in structural defectiveness leads to a decrease of the ordering temperature and to intensive growth of the ordered phase grains at low annealing temperatures, which is the reason of the high coercivity.

Authors of Ref. [37] studied the influence of the additional Au layer thickness and the heat treatment temperature on the ordering process in [FePt(2 nm)/Au(x nm)]$_{20}$ (where x = 0.5–3.5 nm) multilayer stacks deposited onto the thermally oxidized substrates of single-crystal silicon. According to the XRD results, the interplanar $d_{(220)}$ spacing of the disordered $A1$-FePt phase in the as-deposited films increases with increase of Au layer thickness. Therefore, the stored energy of the disordered phase crystal lattice increases, contributing to the acceleration of diffusion during the following annealing. In these films, the ordered phase formation occurs at 300 °C. Films coercivity increases with in-

creasing the thickness of the additional Au layer. It is interesting to note that, in case of elevated heat treatment temperatures (600 °C), the contrary dependence was observed: the ordering parameter of the $L1_0$-FePt phase and the films coercivity decrease with increasing thickness of the Au layer. A similar result was obtained in [38], where authors investigated the effect of the additional Au layers introduction (with thickness of 0.5−3.5 nm) on the ordering rate in [Fe(1 nm)/Pt(2 nm)/Fe(1 nm))/Au(x nm)]$_{10}$ stacks. The ordered $L1_0$-FePt phase was formed after heat treatment at 400 °C, and its amount increases with increasing the thickness of the Au layer. However, an increase in the Au layer thickness in stacks annealed at 500 °C leads to a decrease in the ordering rate.

The influence of additional Cu layers on the ordering temperature in multilayer [Fe/Pt/Cu]$_{18}$ films was investigated in Ref. [39]. The obtained films were treated by rapid thermal annealing in an atmosphere of Ar + H$_2$ mixture in a temperature range 300−500 °C for 60 seconds. It was found that the ordered $L1_0$-FePt phase was already formed at 300 °C in the films with additional Cu layers. At the same time, the ordering starts at 350 °C in the case of Fe/Pt films. The effect of the Cu content on the ordering degree was estimated by the ratio of lattice parameters (c/a) of the ordered phase. It was found that the c/a ratio increases with an increase in the Cu concentration, indicating that a certain amount of Cu (which did not dissolved in FePt) restrains the ordering process.

The decrease in the ordering temperature of 20 nm thick FePt films, deposited onto a thermally oxidized silicon substrate, to 300 °C was achieved in Ref. [40] by introducing a 20 nm thick AgCu underlayer. The coercivity of the films was 5.2 kOe even after annealing at 300 °C, and increased up to 10 kOe after annealing at 400 °C. The authors explain the decrease in the ordering temperature by the stresses arising during the decomposition of the metastable AgCu phase during the heating. It was also found that Cu diffuses into the FePt layer during the annealing, forming ternary $L1_0$-FePtCu compound, which also contributes to the reduction of the ordering temperature.

The decrease of the ordering temperature was reached for [FePt(10 nm)]$_{10}$ films in Ref. [41]. The ordering temperature was reduced from 500 °C to 380 °C by introduction of additional cap- (50 nm) and under- (10 nm) Cr layers. Moreover, an addition of an intermediate Cu layer (0.2 nm thick) to the films with additional Cr layers leads to the further reduction of the ordering temperature to 340 °C. It was found that the Cu and Cr atoms diffuse into FePt layers during annealing, leading to an increase in the diffusion mobility of Fe atoms and, thus, to a decrease in the ordering temperature in the films.

It was established in Ref. [42] that the presence of tensile stresses, arising during heat treatment at the interface between FePt and amor-

phous Ni−Al layers due to the difference in the thermal expansion coefficients, leads to a reduction of the ordering temperature as well. The FePt thin films (90 nm) deposited onto the amorphous Ni−Al (10 nm) layer have a coercivity of 5 kOe after annealing at 380 °C; and the $L1_0$-FePt phase long-range order parameter is 0.67. Whereas, the films deposited onto a SiO_2/Si(001) substrate without a Ni−Al underlayer have a coercivity of 0.4 kOe and a long-range order parameter of 0.35.

It was established in Ref. [43] that the introduction of an additional Al underlayer, having a slight larger lattice parameter than FePt, has a positive effect on the decrease of the $L1_0$-FePt phase formation temperature. Using the analysis of coercivity values, authors [43] determined that the hard magnetic $L1_0$-FePt phase forms after annealing at 350 °C in the layer stacks with a 2 nm thick Al layer. This temperature was 400 °C for the films without additional layer.

In Ref. [44], the authors compared the influence of the cap Ru and Ag layers introduction on the ordering temperature and [001] grains texture formation in FePt thin films. It was found that the introduction of the cap Ag layer results in the reduction of the ordering temperature and formation of the preferred orientation of the grains in the [001] direction. At the same time, the presence of the cap Ru layer increases the ordered $L1_0$-FePt phase formation temperature by ≈ 100 °C comparing with the films without an additional layer. The authors explain this distinction by the difference in the level of stresses arising during heat treatment. While the presence of the Ag layer causes tensile stresses, the presence of the Ru layer causes compressive stresses.

Thus, it can be concluded that the introduction of additional layers of alloying elements into the FePt based films could lead to the reduction of the ordering temperature. However, this influence depends essentially on the nature of the additional component, the initial thickness of the layers, and the conditions of the heat treatment.

Ordering Temperature Reduction by External Magnetic Fields

The application of an external magnetic field during the heat treatment of FePt based films could affect significantly the phase transformations by changing the Gibbs free energy of ferromagnetic phase by the value of $-MH$ (M—magnetization, H—strength of magnetic field) [45–47]. Thus, the change in magnetic energy acts as an additional driving force for the $A1$-FePt $\rightarrow L1_0$-FePt phase transformation in the case when the nuclei of the ordered phase are ferromagnetic, while the $A1$-FePt matrix is paramagnetic. That is why, in order to accelerate the ordering in FePt based films in the presence of an external magnetic field, it is reasonably to use a temperature above the Curie point of the disordered $A1$-FePt phase (330 °C) and below the Curie point of the ordered $L1_0$-FePt phase (480 °C).
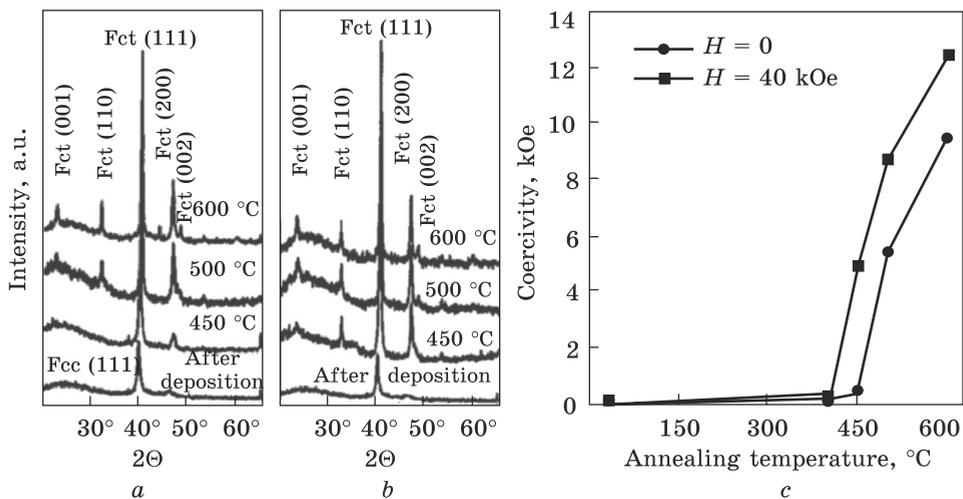
Fig. 4. XRD patterns of FePt(80 nm) films annealed at different temperatures without ($H = 0$ Oe) external magnetic field (*a*) and within the external magnetic field $H = 40$ kOe (*b*); coercivity as a function of annealing temperature (*c*) [46]

Investigation of structural and magnetic properties of 80 nm thick FePt thin films after annealing at 450–600 °C in a magnetic field of 40 kOe was carried out in Ref. [47]. Authors [47] revealed that the onset temperature of the ordering decreases at least by 100 °C in comparison with the annealing without field (Fig. 4, *a*, *b*) [47]. Formation of the ordered $L1_0$-FePt phase was accelerated mainly at an initial stage of the heat treatment. The coercivity of thin films annealed in the magnetic field was always higher as compared to the films after treatment at the same temperature but without external field. This effect authors attributed to a higher ordering degree in the field-annealed films (Fig. 4, *c*).

Preliminary annealing of a thin metastable $FeAg/SiO_2$ film in a magnetic field of 10 kOe was carried out in Ref. [48], followed by deposition of the Pt layer on the film surface. Further, heat treatment in the temperature range of 300–500 °C was performed without a magnetic field in order to form the hard-magnetic $L1_0$-FePt phase. It was found that preliminary annealing in a magnetic field promotes the orientation of Fe particles in the [001] direction as well as an increases their size in comparison to annealing without a field. Fe particles appeared due to its segregation from the metastable FeAg matrix. The XRD results and magnetic-properties' measurements convincingly demonstrate that the deposition of the Pt layer on the Fe layer with a [001] texture results in a reduction of the ordering temperature in the $Pt/FeAg/SiO_2$ thin film as well as in enhancement of its coercivity. In this case, the ordered $L1_0$-FePt phase forms at a temperature of 400 °C.

The above-described results indicate that the heat treatment of films under an external magnetic field is an effective way of reducing the temperature of the $L1_0$-FePt ordered phase formation.

Grains Texture Formation in $L1_0$-FePt Ordered Thin Films

As was already noted, one of the materials science challenges dealing with application of the FePt-based thin films as a magnetic high-density recording medium is the orientation of the easy magnetization axis perpendicularly to the film plane. That is why, it is required to form the [001] grains texture in the ordered FePt thin films.

In many works, in order to form [001] grains texture, it is proposed to control thermal tensile stresses in films by introduction of additional underlayers of materials, whose thermal expansion coefficient exceeds the corresponding coefficient of the FePt.

The FePt(15 nm)/Ag(50 nm) thin film deposited onto a glass substrate were annealed at 550 °C for 30 minutes in work [20]. As a result, a preferred orientation of the grains in the [001] direction was obtained [20]. According to XRD results, it was determined that the grains texture coefficient takes a maximum value in the films with a 50 nm thick Ag underlayer, and decreases with the reduction of the sublayer thickness. The positive effect of the Ag underlayer on grains texture formation is explained by the influence of tensile stresses arising at the interface between the metal layers since the lattice parameter of Ag exceeds the parameter of the FePt lattice by 5.5%.

Authors of the work [49] investigated the effect of the mismatch degree between the lattice parameters of the film and the single-crystal substrate on the grains texture formation. FePt films (10 nm thick) were deposited onto single-crystal MgO(001) and $MgAl_2O_4$(001) substrates at 700 °C. The mismatch between the lattice parameters of the substrates and the ordered $L1_0$-FePt phase was 9.6% and 4.9%, respectively. It was found that there are grains of the ordered phase with orientations in both [001] and [010] directions in the film on the $MgAl_2O_4$ substrate. According to the XRD data, the d-spacing, $d_{(002)}$, of the $L1_0$-FePt phase in the FePt/$MgAl_2O_4$ film is larger in comparison with the corresponding d-spacing in film on the MgO substrate. Based on the obtained results, the authors concluded that a decrease in the mismatch between the lattice parameters of a metal film and a single-crystal substrate leads to the appearance of tensile stresses oriented along the normal to the film plane. This effect causes an increase in the d-spacing, $d_{(002)}$, and orientation of the easy magnetization axis in the film plane.

Recently the rapid thermal annealing method attracted much attention of researchers as an effective approach for reducing the ordering temperature and formation of the desired grains texture in FePt-based thin films [50, 51]. For example, in Ref. [51], the ordered $L1_0$-FePt
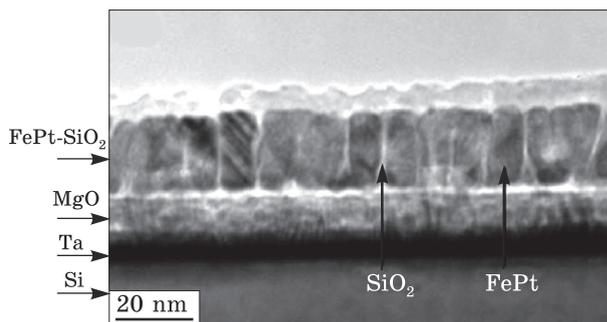
FePt-SiO$_2$

MgO

Ta

Si

20 nm

SiO$_2$ FePt

Fig. 5. Cross-section transmission electron microscopy image of the thin FePt–SiO$_2$/MgO/Ta/Si film deposited at 470 °C [52]

phase was obtained with a preferred grains orientation in the [001] direction after rapid thermal annealing at 600 °C for 5 seconds of FePt/SiO$_2$/Si(001) films. This effect was explained by the appearance of tensile stresses due to the difference in the thermal expansion coefficients of a FePt film and a Si single-crystal. More light emitted by the annealing lamps was absorbed by the monocrystalline substrate during the heat treatment since Si has a larger light absorption coefficient. This leads to a larger thermal expansion of silicon in comparison with the metallic film. It was noted that, for the present experiment conditions, in order to achieve a high value of magnetocrystalline anisotropy, the optimal thickness of the film should be in the range of 5−10 nm. Decrease of the thin film thickness leads to a decrease in the ordering degree, while an increase of the thickness results in the degradation of [001] grain texture.

The introduction into the FePt-based films of such oxides as ZrO$_2$ [52], SiO$_2$ [53, 54], TiO$_2$ [55−57] and Ta$_2$O$_5$ [57] promotes formation of the ordered $L1_0$-FePt phase with magnetically isolated columnar grains.

For example, in Ref. [53], the ordered $L1_0$-FePt phase with columnar magnetically isolated grains was obtained by the alternation deposition of the FePt alloy and SiO$_2$ oxide at a substrate temperature of 470 °C. The films were deposited onto an MgO/Ta sublayer; monocrystalline silicon was used as a substrate. It could be clearly seen from electron microscopy image (Fig. 5) that the grains of the ordered $L1_0$-FePt phase in the films with the SiO$_2$ addition have a columnar shape and are separated from each other by a uniform thin oxide layer. The coercivity of the films was 7 kOe and the grain size of the $L1_0$-FePt phase was 7 nm. In addition, the authors [53] investigated the effect of the MgO oxide addition on the grain structure of the films obtained under similar conditions. It was determined that the addition of SiO$_2$ oxide to FePt-based films allows obtaining smaller grains of the ordered phase comparing with the MgO-alloyed films. It was also found that, when the volume fraction of the MgO oxide is reduced (<30%), the columnar grain structure is not formed. At the same time, columnar grains could be obtained even with 15 vol.% of SiO$_2$.

Reference [58] reports that the addition of 35 vol.% of ZrO_2 oxide to FePt films allowed to obtain the ordered $L1_0$-FePt phase with the following parameters of the columnar grains: 5.6 nm in size with the ratio of the grain height to its width of 2.6. The films were obtained by deposition (at 500 °C) on glass substrate using TiON/TiN/CrRu(30 nm) sublayers. It was found that the ZrO_2 oxide does not interact with the ordered $L1_0$-FePt phase. During the film deposition, ZrO_2 occupies positions along the grain boundaries, resulting in magnetic insulation of ferromagnetic grains. However, such isolation is partial in this case; according to the electron microscopy study, the grains of the ordered phase have a labyrinth structure. Moreover, there are not only grains with [001] orientation in the film, formed because of the epitaxial growth of the $L1_0$-FePt phase on the TiON sublayer but [111] oriented grains as well. The amount of grains oriented in the [001] direction could be significantly increased in these films by the addition of 5 vol.% of C.

Authors of Ref. [59] carried out a complex study of the effect of alloying with amorphous (TiO_2, SiO_2, MgO, C) and crystalline (HfO_2 and ZrO_2) compounds on the microstructure of FePt thin films. Thin FePt(6 nm)/X (30 vol.%) films (X = TiO_2, SiO_2, MgO, C, HfO_2 and ZrO_2) were obtained by magnetron deposition onto TiON/TiN/CrRu(30 nm)/ glass layers at 500 °C. It was found that the introduction of amorphous compounds (especially MgO and C) into the FePt films leads to the formation of a preferred grains orientation of the ordered $L1_0$-FePt phase in the [001] direction as well as their magnetic isolation, rather than alloying with crystalline compounds. Nevertheless, the grains of the $L1_0$-FePt phase have a well-defined columnar shape in case of alloying with crystalline HfO_2 and ZrO_2, while alloying with amorphous compounds leads to the formation of spherical grains. It was also found that, in the FePt films alloyed with ZrO_2, there are grains of the ordered phase oriented in the [200] direction that is a result of the epitaxial growth of these grains on crystalline ZrO_2. In the case of crystalline HfO_2 instead of ZrO_2, the amount of $L1_0$-FePt phase grains with the [001] orientation was substantially increased [60]. This distinction is attributed to the higher mismatch between the HfO_2 and FePt lattice parameters (about 25−28%). Because of this reason, there is no epitaxial growth of the ordered phase grains on the HfO_2 oxide.

Application of an external magnetic field during heat treatment of thin films also promotes the formation of a pronounced [001] grains texture of the ordered $L1_0$-FePt phase, leading to the corresponding orientation of the easy magnetization axis. A two-stage annealing of Pt(2 nm)/FePt(20 nm)/Fe(2 nm)/Si thin films was carried out in Ref. [61], in order to separate the effect of stresses arising at the stage of the ordered phase formation and the effect of a magnetic field on the formation of [001] grains' texture. Thin films were annealed at 700 °C
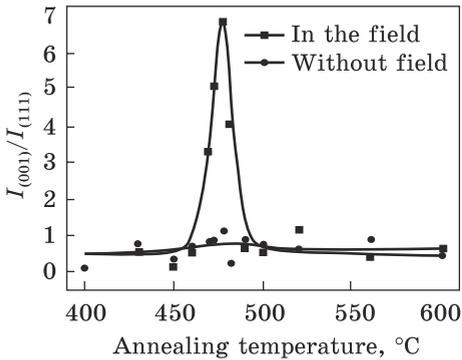
Fig. 6. The (001) and (111) diffraction peaks intensities ratio *vs.* annealing temperature for Pt(2 nm)/FePt(20 nm)/Fe(2 nm)/Si film [60]

for 30 minutes to form the ordered $L1_0$-FePt phase at the first stage. Subsequent annealing was carried out in a wide temperature range (400–600 °C) for 1 hour under an external magnetic field of 35 kOe applied in the perpendicular to the film plane direction. A similar annealing without a field was also carried out. An annealing in a magnetic field at a temperature close to the Curie temperature of the $L1_0$-FePt phase (480 °C) promotes orientation of the easy magnetization axis along the direction of the applied field. The texture of the grains was estimated from the intensity ratio of the diffraction (001) and (111) peaks. This ratio is maximal at 478 °C. The [001] grains texture was not occurred after annealing at temperatures below 450 °C and above 500 °C (Fig. 6).

In a number of works, it was also shown that annealing in a magnetic field leads to a decrease in the grain size of the ordered FePt phase and to more sharp grain size distribution [62–64]. For example, in case of a heat treatment of thin FePt films at 500 °C in a magnetic field of 20–40 kOe, the grain size of the ordered phase decreases by a factor of two as compared to the films annealed without the field [62]. The authors [62] also determined that the number of nuclei of the ordered phase is proportional to the external magnetic field. However, with an increase of the magnetic field (>60 kOe), a rapid rise in the grain size of the ordered phase was observed. This fact was explained by the high density of formed nuclei and their coalescence during annealing.

Thus, it can be seen that there are a large number of proposed methods to provide the required parameters of the ordered $L1_0$-FePt phase grains structure in modern scientific literature, allowing reaching the desired properties.

Tuning the Magnetic Properties of the Ordered $L1_0$-FePt Phase

Currently, studies related to the magnetic properties control of the FePt-based films are carried out in two main directions. The first direction is related to the increase in the coercivity of these films. The second one is related to creation of exchange spring and phase graded film structures.

Coercivity Enhancement

The coercivity of FePt-based thin films, which directly affects the thermal stability of the recording medium, can be enhanced by decreasing the exchange magnetic interaction between neighbouring grains of the ordered $L1_0$-FePt phase. Magnetic insulation of ferromagnetic grains can be provided by grain boundaries saturation with a nonmagnetic material. For example, this approach was used in the studies discussed above [53, 58–60] using oxide compounds, or metals such as Au and Ag. A substantial increase in the coercivity of annealed Pt/Ag/Fe films in comparison with bilayer Pt/Fe films was obtained in Ref. [65]. The authors explain the observed effect by the magnetic isolation of the ordered $L1_0$-FePt phase grains due to grain-boundary diffusion of Ag in the direction of the film surface during heat treatment.

The coercivity of thin FePt films can be significantly increased by introducing an additional top Au layer [66] as well. The Au(60 nm)/FePt(60 nm) films were deposited by magnetron sputtering in two stages. First, a FePt layer was deposited onto a substrate at 800 °C, in order to form the ordered $L1_0$-FePt phase. Then, an Au layer was deposited onto a surface of the obtained film at room temperature. The obtained bilayer film was annealed for 1 hour at 800 °C. The XRD data showed that, after annealing of the bilayer film, the ordering degree and the lattice parameters of the $L1_0$-FePt phase remained unchanged comparing to the films without an Au layer, indicating the Au insolubility in the $L1_0$-FePt matrix. The coercivity of films with the top Au layer increases up to 20 kOe, while single-layer films are characterized by coercivity about 15 kOe. The authors explain this effect by the magnetic insulation of the $L1_0$-FePt grains due to Au diffusion along the grain boundaries of the ordered phase during heat treatment, which was confirmed by the transmission electron microscopy study.

Phase Graded and Exchange Spring Thin Films

For data recording, the magnetic field created by the recording head must exceed the coercivity of the medium layer. This restriction becomes a problem when high-coercivity materials are used as a storage medium. To overcome this obstacle, researches currently develop new recording methods such as heat-assisted magnetic recording [67, 68] and microwave-assisted magnetic recording [69].

The solution of this problem is also possible by using multilayer exchange spring media as the data carrier. In exchange spring media, the thermal stability of the recorded data is provided by a hard magnetic component, while the domain magnetization reversal is provided by a soft magnetic one [70–73]. The magnetization reversal of ferromagnetic domains in such films is occurred stage-by-stage. First, under
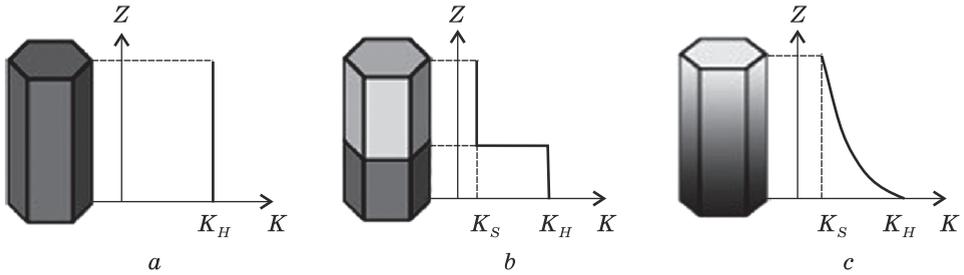
Fig. 7. Schematic illustration of a single-phase ferromagnetic grain (*a*), exchange spring grains (*b*) and graded media (*c*), where K_S is the anisotropy constant of the soft phase and K_H is the anisotropy constant of the hard phase [81]

an external magnetic field, the magnetic domain walls are formed in the soft magnetic layer, and then, these walls become pinned at the interface between the soft and hard magnetic phases. Then, if the external magnetic field exceeds a certain threshold value, further growth of the domain walls occurs already in the layer of high-coercive material [74]. The thermal stability of the carrier depends only on the coercivity of the hard magnetic phase despite the decrease in the strength of the external magnetic field required for magnetization reversal of the exchange spring films.

Formation of the graded media with a nonuniform distribution of magnetic properties along their thickness (a gradual transition from a hard magnetic phase to a soft one without a sharp interface between them) is being investigated as well (Fig. 7). The change in the magnetization of such structures requires the application of a magnetic field of even lower intensity in comparison with exchange spring films [75–82], keeping the stability of the recorded data.

The author of Ref. [83] obtained a layered exchange spring FePt/FeAu films, where the magnetic interaction between the FeAu soft magnetic layer and the $L1_0$-FePt hard magnetic layer results in reduction of the magnetic field required for the magnetization reversal of the high-coercive phase domains. The FePt(20 nm)/FeAu(0, 5, 10, 20 nm) thin films were deposited onto a glass substrate and post-annealed for 1 hour at 400 °C and 550 °C. It was found that the introduction of the FeAu underlayer reduces the ordering temperature by 150 °C due to the stresses. These stresses arise from the difference in the thermal expansion coefficients of the FePt and FeAu layers. Furthermore, the generation of additional crystal structure defects during Au diffusion to the film surface upon the heat treatment also contributes to the ordering temperature reduction. It was shown that the thickness of the FeAu underlayer significantly affects the value of the bilayers coercivity. As the thickness of the FeAu layer increases, the coercivity rapidly decreases due to the magnetic exchange interaction between the layers. It

is interesting that the coercivity of films annealed at 400 °C is higher than after annealing at 550 °C, which could be explained by the more intense diffusion of Au into the FePt layer at the higher temperature. Thus, the approach proposed in this paper is effective for creation of exchange spring FePt based films with a graded interface between hard and soft magnetic layers.

It is known that the alloying of FePt based films with additional components forming ternary compounds with the $L1_0$-FePt phase could lead to degradation of the hard magnetic properties [84–86]. The effect of decreasing the magnetocrystalline anisotropy of the $L1_0$-FePt ordered phase with an increase in the Mn content [86] was used in Ref. [79] to create a phase-graded media. The FePt(25 nm)/PtMn(50 nm) layers were deposited on single-crystal MgO(001) substrates at 500 °C and then heat-treated at 550 °C. As a result, a gradient distribution of the coercivity over the film thickness was obtained [79]. The XRD results indicate that, after deposition and annealing, all films have a clearly pronounced preferred orientation of the grains of both phases in the [001] direction, indicating the epitaxial growth of both layers on the MgO(001) substrate. The PtMn layer serves as a source of Mn, which diffuses into the FePt layer during the heat treatment, forming a ternary $Fe_{50-x}Mn_xPt_{50}$ compound. The concentration gradient of Mn over the FePt layer thickness causes the occurrence of a coercivity gradient. However, the exchange springing between the antiferromagnetic PtMn layer and the $Fe_{50-x}Mn_xPt_{50}$ layer results in the coercivity increase of the latter. The value of this 'additional' coercivity decreases with increasing distance from the interface between FePt/PtMn layers. Thus, in this film, the gradient of the magnetic properties is not uniform throughout the entire thickness.

In a number of studies, authors propose a reduction of the substrate temperature during the film deposition as a method for creating an exchange spring media [76, 80, 81]. For example, in Ref. [80], the initial 11.5 nm of FePt alloy were deposited on a monocrystalline MgO(001) substrate at 700 °C in order to form the $L1_0$-FePt phase. Thereafter,

Table 2. **Deposition conditions and magnetic properties of the samples obtained in Ref. [76]**

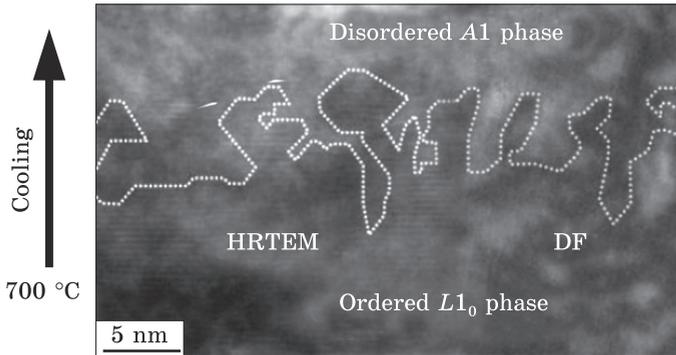| Sample	t_{grad}, nm	T_{final}, °C	Cooling rate, °C/min	H_c, kOe	Remanence magnetization (M_r/M_s)
$L1_0$-FePt	0.00	700	—	33.2	0.98
A	2.31	600	43.5	32.1	0.96
B	11.1	600	9.01	4.00	0.94
C	10.0	450	25.0	9.62	0.98
D	37.5	262	11.7	1.25	0.45

Fig. 8. High-resolution transmission electron microscopy image of the exchange spring media obtained in Ref. [79]

while cooling the substrate to different final temperatures (T_{final}), the FePt layer was deposited on the top, and the thickness of this FePt layer was varied (t_{grad}). According to the transmission electron microscopy results, the structure of the upper layer deposited at the substrate cooling is a gradient transition from the $L1_0$-FePt hard magnetic phase to the soft $A1$-FePt one. The values of the coercivity presented in Table 2 show that the presence of such a 'transition' layer (2.31 nm thick) does not significantly affect the film coercivity as compared to the fully ordered films. At the same time, the increasing the thickness of this layer up to 10 nm and 11.1 nm leads to the reduction of the coercivity by 70.1% and 87.6%, respectively. The remanence of films almost does not change with varying thickness of the 'transition' layer. A significant decrease in the remanence is observed in a D sample (see Table 2 and Fig. 8), which is explained by the much larger thickness of the 'transition' layer comparing with the layer thickness of the ordered $L1_0$-FePt phase. It was also shown that the roughness of the interface between the ordered phase and the 'intermediate' layers increases with decreasing cooling rate of the substrate during the second stage of the deposition.

A similar method was used in [76] in order to obtain exchange spring $A1/L1_0$-FePt films deposited on MgO(2 nm)/Cr(50 nm) underlayer. It was found that, with an increase in the thickness of the 'transition' layer, the films coercivity decreases. At the 'transition' layer thickness of 5 nm, the coercivity was reduced by 30% as compared to the fully ordered films. It was also shown that the grains of the ordered phase have a preferred orientation in the [001] direction with an increased thickness of the 'transition' layer to 15 nm. The [001] grain texture degrades at large thicknesses of this layer.

Thus, FePt-based films with a graded distribution of the magnetic properties over the film thickness could be obtained by various methods, particularly, using the features of the diffusion interaction of additional alloying elements with the ordered $L1_0$-FePt phase under the heat treatment or by varying parameters of thin films deposition.

Conclusions

Thin films based on the ordered $L1_0$-FePt phase attract the attention of researchers as a material for magnetic storage media with ultrahigh density due to the high energy of the magnetocrystalline anisotropy of this phase ($7 \cdot 10^6$ J/m³).

The analysis of recent studies has revealed that the formation of desired properties of ordered $L1_0$-FePt phase could be achieved by various materials science approaches. Particularly, these approaches are as follow.

(a) It is an increase in the level of the initial stresses in the films by varying the number of interfaces, the degree of mismatch between the lattice parameters of the metal layers and the substrate, and a control of the stresses arising during heat treatment due to the difference in thermal expansion coefficients of the film and substrate/additional layer. Compressive mechanical stresses could lead to a reduction of the ordering temperature.

(b) It is an alloying with additional elements, whose influence on the ordering temperature, grains structure and magnetic properties of the films significantly depends on the interaction mechanism of these elements with the ordered $L1_0$-FePt phase.

(c) It is an additional layers introduction into the films, depending on the composition and configuration of which, the grain texture, magnetic properties and the ordering temperature could be substantially changed *via* the heat treatment.

(d) It is the application of an external magnetic field during the deposition and/or heat treatment of thin films, promoting the reduction of the ordering temperature as well as the formation of a preferred orientation of the $L1_0$-FePt grains in the direction of field lines.

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МАТЕРІЯЛОЗНАВЧІ АСПЕКТИ
ФОРМУВАННЯ ТОНКИХ ПЛІВОК НА ОСНОВІ FePt

Метою даного огляду є аналіза основних фізико-матеріялознавчих метод досягнення наперед заданих властивостей нанорозмірних плівкових матеріялів на основі FePt. Досягнення таких властивостей потрібне задля промислового використання даних матеріялів у якості середовища магнетного запису та зберігання інформації з надвисокою щільністю. Наведено результати досліджень, в яких розглядаються різноманітні підходи до вирішення таких завдань як зменшення температури впорядкування, формування потрібної кристалографічної орієнтації зерен впорядкованої фази, підвищення коерцитивної сили та забезпечення можливости контрольованої зміни намагнетованости даних матеріялів.

Ключові слова: впорядкована фаза $L1_0$-FePt, фазові перетворення, тонкі плівки, магнетний запис.

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МАТЕРИАЛОВЕДЧЕСКИЕ АСПЕКТЫ
ФОРМИРОВАНИЯ ТОНКИХ ПЛЁНОК НА ОСНОВЕ FePt

Целью данного обзора является рассмотрение основных физико-материаловедческих методов обеспечения наперёд заданных свойств наноразмерных плёночных материалов на основе FePt. Достижение таких свойств необходимо для промышленного использования данных материалов в качестве среды магнитной записи и хранения информации со сверхвысокой плотностью. Приведены результаты исследований, в которых рассмотрены различные подходы к решению таких задач как снижение температуры упорядочения, формирование необходимой кристаллографической ориентации зёрен упорядоченной фазы, повышение коэрцитивной силы и обеспечение возможности контролируемого изменения намагниченности данных материалов.

Ключевые слова: упорядоченная фаза $L1_0$-FePt, фазовые превращения, тонкие плёнки, магнитная запись.