THICKNESS DEPENDENCIES OF THE COERCIVITY OF THREE-LAYER MAGNETIC FILMS OBTAINED BY CHEMICAL DEPOSITION

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Received November 15, 2024

Revised December 14, 2024

Accepted December 30, 2024

Abstract. The results of the study of the coercivity of three-layer magnetic films obtained by chemical deposition are presented. The features of its changes from the thickness of the forming layers are determined. They are associated with the specificity of the magnetization reversal of the studied system, caused by a small difference in the values of the coercivity of the magnetic layers. The energy of the demagnetizing field is calculated, since an expression for the critical field for the magnetization reversal of the film is obtained, which describes well the experimentally observed linear dependence of the coercivity on the thickness of the magnetic layers.

Keywords: *multilayer magnetic films, coercivity, interlayer interaction, demagnetizing field*

DOI: 10.31857/S03676765250404e9

INTRODUCTION

Interesting from the physical and applied points of view is the effect of a significant decrease in the coercivity, which is found in multilayer films separated by a nonmagnetic interlayer. The physical mechanisms of the observed changes in the coercivity H_C are mainly attributed to the interaction of domain boundaries separating domains in neighboring magnetic layers. This leads to a decrease in the total energy of domain walls and a decrease in H_C. For the first time, a decrease in the coercivity in layered structures in the presence of a nonmagnetic interlayer was observed in polycrystalline films in which Ni layers are separated by Cu [1]. A similar effect was found in trilayer films containing two layers of $Ni_{80}Fe_{20}$, which are separated by a non-magnetic interlayer of either silicon [2] or silicon oxide [3]. The mechanisms of H_C reduction in trilayer films mainly consider the magnetostatic interaction of domain walls in magnetic layers through a nonmagnetic interlayer (the Neel model) [4,5].

The aim of the present work is to elucidate the physical mechanisms of change in the coercivity of three-layer films obtained by chemical deposition depending on the thickness of the non-magnetic interlayer and magnetic layers.

It is shown that the observed changes in the coercive force in the studied systems are related to the peculiarities of exchange coupling and magnetostatic interaction between magnetic layers.

EXPERIMENTAL RESULTS

Three-layer films obtained by chemical deposition [6,7] contained magnetic layers of equal thickness made of amorphous Co-P alloy, and an intermediate layer made of non-magnetic amorphous Ni-P alloy.

The thickness of the layers was determined by the deposition time at a rate, which was set by X-ray spectral analysis, for amorphous Co-P was 6 Å/s, Ni-P was 2 Å/s, and crystalline Co-P was 5 Å/s. The thickness of the magnetic layers varied from 10 to 180 nm, the non-magnetic interlayer from 0 to 10 nm. The layers were deposited in a homogeneous magnetic field with the strength H= 1 kE, by means of which uniaxial anisotropy was created.

The value of the coercive force was established using the Kerr meridional magneto-optical effect at 0.01 Hz and a vibrating magnetometer at room temperature. The dimensions of the films were 5× 5 mm^2.

A peculiarity of the studied samples is a small difference in the coercive forces between the magnetic layers, which is manifested in the hysteresis loop displacement when the film is remagnetized in small fields [8]. As the thickness of the interlayer t increases, the value of the displacement field $H_B$grows up to 4 Å, then decreases and in the region t ~ 2 nm falls to 0 and changes sign to negative (Fig. 1).

The coercivity also experiences a non-monotonic dependence on the thickness of the interlayer. When it changes from 0 to 2 nm, the value of $H_C$decreases from 9.5 to 1.4 E, then grows and reaches 3.3 E at t~ 8 nm (Fig. 1).

Further reduction of the coercivity of such a structure can be achieved by increasing the thickness of magnetic layers (Fig. 2). Its value decreases linearly with increasing *d* and reaches ~ 0.05 E at a magnetic layer thickness of ~ 200 nm (the thickness of the interlayer was ~ 2 nm).

The thickness dependence of the coercivity of single-layer CoP films is shown in the same figure for comparison. The observed maximum of its values at film thicknesses in the region of 60 nm is obviously related to the transition of the domain boundary structure from the Neulevsky to Bloch type, as in the case of permalloy films.

DISCUSSION OF EXPERIMENTAL RESULTS AND THEIR THEORETICAL SUBSTANTIATION

The presented results differ from previously reported variations of the coercivity in three-layer systems [8], in which a nonmonotonic dependence of the coercivity on the thickness of magnetic layers was observed. As follows from this work, in the region of small thicknesses of the interlayer, the imperfection of the interlayer over the film area has a great influence on the configuration of domain boundaries and their energy , which leads to a non-monotonic dependence of the coercivity on the interlayer thickness.

As noted above, the peculiarity of our samples is the small differences in the values of the coercive forces of the magnetic layers, which is well reflected in the hysteresis loop (Fig. 3). In the vicinity of the saturation field, it shows a step, which is associated with the additional field required for the remagnetization of the higher coercivity layer. This indicates that the remagnetization of the film occurs in two steps; in the initial step, domains of reverse magnetization appear in the less coercive layer and their subsequent growth. The final remagnetization of the film ends with the reversal of magnetization in the more highly coercive layer. This mechanism is confirmed in three-layer films with magnetic layers made of CoP, which differ significantly in the magnitude of the coercivity [7]. The variation of the coercivity with the thickness of the interlayer in such films occurs in a similar way as in the samples studied here.

The total energy of the three-layer system in the geometry shown in Fig. 5, can be defined in the form:

$$W = W_Z + W_f + W_M, \tag{1}$$

where , ,W_Z W_f W_M are the Zeeman, exchange ferromagnetic and magnetostatic interaction energies between magnetic layers. The contribution of the ferromagnetic interaction and its change from the paramagnetic layer thickness was considered earlier in [9].

For theoretical substantiation of the changes of the coercive force from the thickness of magnetic layers, we find the demagnetizing energy in two cases: a) the magnetizations of magnetic layers are antiparallel, b) parallel to each other.

In the first case, magnetic charges with surface density $\pm\sigma$ (Fig. 4) appear at the film ends, which coincide with the XY plane.

The average surface magnetostatic energy density can be estimated from Eq:

$$W_M = \frac{1}{2d}\int_0^{2d+t} \sigma\varphi(x,z)\,dx, \tag{2}$$

where $\varphi(x,z)$ is the potential created by magnetic charges.

In fact, the problem for determining W_M is reduced to determining the dependency of $\varphi(x,z)$ [10].

Details of the calculations of this function in the cases of antiparallel and parallel orientations of magnetic moments are given in the appendix.

The demagnetizing field energy taking into account the obtained expressions for $\varphi(x,z)$ at antiparallel orientation of magnetizations of magnetic layers is represented in the form:

$$W_1 = \frac{2d\sigma^2(2+t')^2}{\pi^2 d}\sum_{n=1}^{\infty}\frac{1}{n^3}\left[\cos^2\left(\frac{\pi n}{2}\right)\sin^2\left(\frac{\pi n}{2}\frac{1+t'}{2+t'}\right)\sin^2\left(\frac{\pi n}{2}\frac{1}{2+t'}\right)\right]. \quad (3)$$

For parallel orientation:

$$W_2 = \frac{2d\sigma^2(2+t')^2}{\pi^2 d}\sum_{n=1}^{\infty}\frac{1}{n^3}\left[\sin^2\left(\frac{\pi n}{2}\right)\cos^2\left(\frac{\pi n}{2}\frac{1+t'}{2+t'}\right)\sin^2\left(\frac{\pi n}{2}\frac{1}{2+t'}\right)\right], \quad (4)$$

where *d* is the thickness of the magnetic layer, *t* is the thickness of the interlayer, $t'= t/d$.

The difference in the energies (3) and (4), which leads to demagnetization of the system, is of the form:

$$\Delta W = \frac{2d\sigma^2(2+t')^2}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^3}\sin^3\left(\frac{\pi n}{2}\frac{1}{2+t'}\right)\sin\left(\frac{\pi n(3+2t')}{2+t'}\right). \quad (5)$$

The value of the coercive force of the three-layer film, taking into account (1), can be determined:

$$H_C = H_{C1} + \Delta H_f - \Delta H_M. \quad (6)$$

The value $H_{(C)\ (1)}$ corresponds to the coercive force of the single-layer film, the added values ΔH_f, ΔH_M- are related to the ferromagnetic and magnetostatic interaction between the magnetic layers.

The contribution of the magnetostatic interaction to (6) can be estimated from the relation:

$$V \cdot M_S \cdot \Delta H_M = \Delta W \cdot S\,, \tag{7}$$

where ,$V = ad\ell$ $S = ad$ are the volume and cross-sectional area of the magnetic layer as shown in Fig. 5.

Then from (5) we find:

$$\Delta H_M = \frac{2dM_S(2+\frac{t}{d})^2}{\pi^2\ell}\sum_{n=1}^{\infty}\frac{1}{n^3}\sin^3\left(\frac{\pi n}{2}\frac{1}{2+\frac{t}{d}}\right)\sin\left(\frac{\pi n}{2}\frac{3+2\frac{t}{d}}{2+\frac{t}{d}}\right). \tag{8}$$

Given the finite value of the series for the case $t \ll d$ we find :

$$\Delta H_M \approx \frac{4,2 \cdot M_S d}{\pi^2 l}\ . \tag{9}$$

Then.

$$H_C \approx H_{C1} - \frac{4.2 M_S d}{\pi^2 l}\,. \tag{10}$$

It follows from the presented expression that the dependence of the coercive force on the thickness of the magnetic layer varies according to a linear law, which qualitatively agrees with the experimental results (see Fig. 2).

CONCLUSION

From the experimental and theoretical results obtained, we can conclude that the observed linear dependence of the coercivity reduction on the thickness of the nonmagnetic interlayer in the three-layer films obtained by chemical deposition can be associated with a small difference in the coercivity values of the magnetic layers, which leads to non-simultaneous remagnetization of the magnetic layers: first, the less coercive layer is remagnetized, and then the more coercive layer is remagnetized. It should be noted that this mechanism of coercivity reduction in low coercivity three-layer films provides a possibility of obtaining magnetic materials with low coercivity.

APPENDIX

$$W = \frac{1}{2d}\int_0^{2d+t} \sigma\varphi dx \tag{11}$$

The potential ϕ satisfies the Laplace equation:

$$\frac{\partial^2\varphi}{\partial^2 x} + \frac{\partial^2\varphi}{\partial^2 z} = 0 \tag{12}$$

With boundary conditions:

$$\frac{\partial\varphi}{\partial z}_{+0} - \frac{\partial\varphi}{\partial z}_{-0} = -\sigma \qquad \text{or} \, . \frac{\partial\varphi}{\partial z}_{-0} = \frac{\sigma}{2} \tag{13}$$

It is reasonable to represent the solution of equation (12) as a Fourier series:

$$\varphi(x,z) = \sum_{n=1}^{\infty}\varphi_{0n}\sin\left(\frac{\pi n}{2d+1}x\right)e^{\frac{\pi n}{2d+1}z} \tag{14}$$

This equation satisfies (1) identically. The constants φ_{0n} are determined from the boundary conditions:

$$\frac{\partial\varphi}{\partial z}_{z=0} = \sum_{n=1}^{\infty}\varphi_{0n}\frac{\pi n}{2d+1}\sin\left(\frac{\pi n}{2d+1}x\right)e^{\frac{\pi n}{2d+1}z} \to \begin{cases} \frac{\sigma}{2}\ npu\ \ 0 < x < d \\ 0\ \ npu\ d < x < d+t \\ -\frac{\sigma}{2}\ npu\ d+t < x < 2d+t \end{cases} \tag{15}$$

Let us take (15) in the form:

$$\varphi(x,z)=\sum_{n=1}^{\infty}\varphi_{0n}n\sin\left(\frac{\pi n}{2d+1}x\right)=0; \qquad \frac{\sigma(2d+t)}{2\pi n}; \qquad f(x) \tag{16}$$

In the right part of this equation is a piecewise function, which we decompose into a series of sines. The coefficients $\varphi_{0n}\cdot n$ before the sines in the left part (16) are the coefficients of the Fourier series, which we determine according to the standard methodology:

$$\begin{aligned}
\varphi_{0n}\cdot n &= \frac{1}{\pi}\cdot\left[\int_0^d \frac{\sigma(2d+t)}{2\pi}\sin(\frac{\pi n}{2d+1}\cdot y)dy-\frac{\sigma(2d+t)}{2\pi}\int_{d+t}\sin(\frac{\pi n}{2d+1}\cdot y)dy\right]\\
&=\frac{\sigma(2d+t)}{2\pi n}\left[\cos\left\{\frac{\pi n}{2d+1}y\right\}\mathrm{I}_d^0-\cos\left\{\frac{\pi n}{2d+1}y\right\}\mathrm{I}_{2d+t}^{d+t}\right]=\\
&=\frac{\sigma(2d+t)}{2\pi n}\left[1-\cos\left\{\frac{\pi n}{2d+1}\right\}-\cos\left\{\frac{\pi n(d+t)}{2d+1}\right\}+\cos(n\pi)\right]\\
\varphi_{0n} &= \frac{d\sigma(2d+t')}{2\pi n^2}\left[1-\cos\left\{\frac{\pi n}{2d+t'}\right\}-\cos\left\{\frac{\pi n(1+t')}{2+t'}\right\}\cos\{\pi n\}\right]
\end{aligned} \tag{17}$$

Where $.t'=\frac{t}{d}$

Taking into account (17) for the potential (14) we can write:

$$\varphi(x,z)=\sum_{n=1}^{\infty}\frac{d\sigma(2d+t')}{2\pi n^2}\left[1+\cos\{\pi n\}-\cos\left\{\frac{\pi n}{2+t'}\right\}-\cos\left\{\frac{\pi n(1+t')}{2+t'}\right\}\right]\sin\left\{\frac{\pi n x'}{2+t'}\right\}e^{\frac{\pi n z'}{2+t'}} \tag{18}$$

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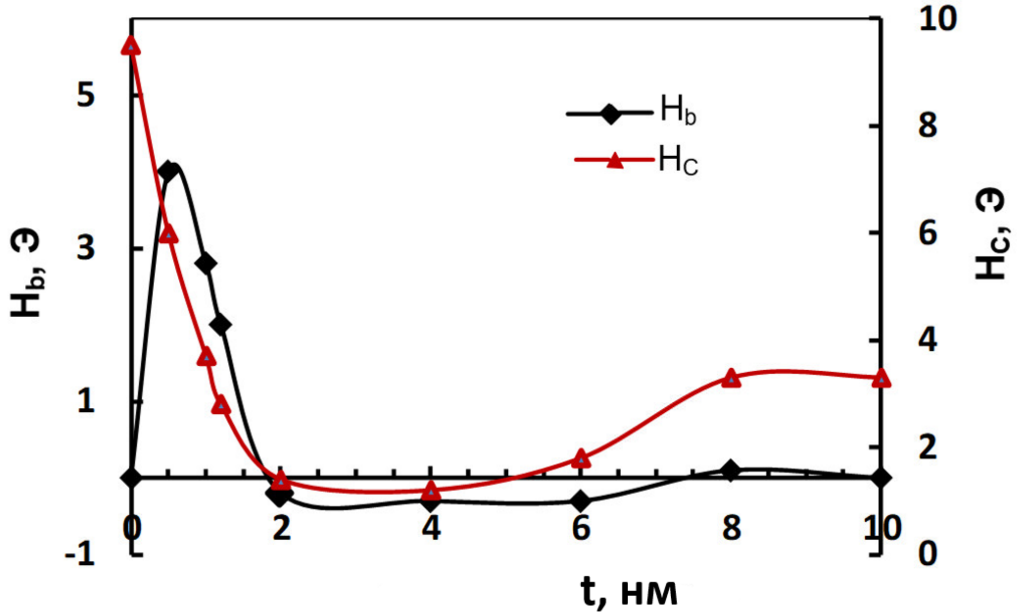
FIGURE CAPTIONS

Fig. 1. Dependence of the displacement field and coercivity on the thickness of the interlayer. The thickness of the magnetic layer is ~100 nm.

Fig. 2. Dependence of the coercive force on the thickness of magnetic layers for three-layer (■) and one-layer (△) films based on CoP.

Fig. 3. Hysteresis loop of the three-layer film based on CoP.

Fig. 4. Orientation of magnetization and magnetic charges in a three-layer film. The light magnetization axis is parallel to *OZ*.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Hb, Э
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Fig. 1

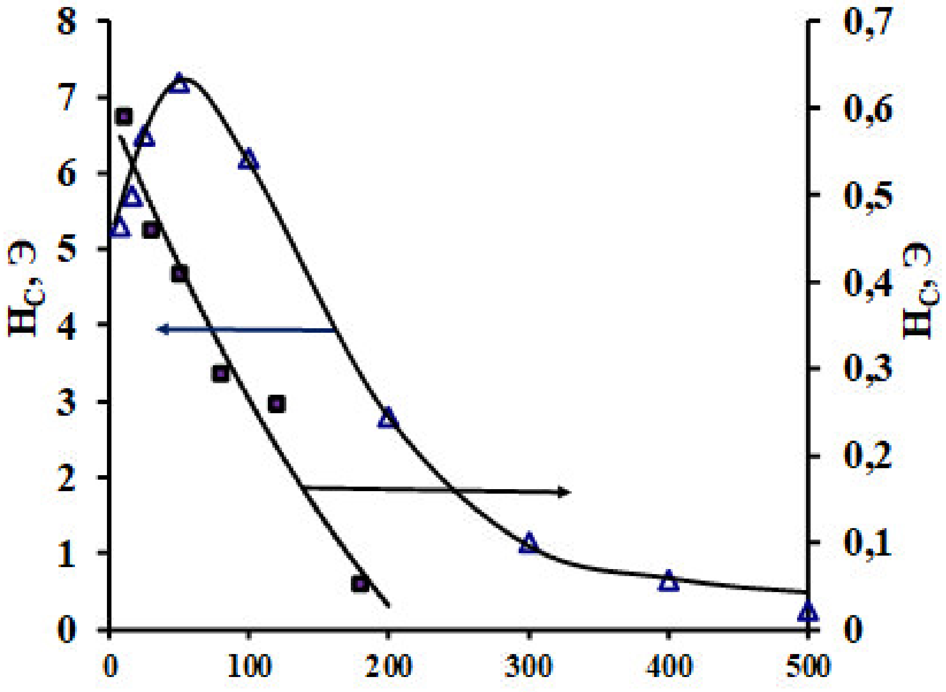
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Fig. 2

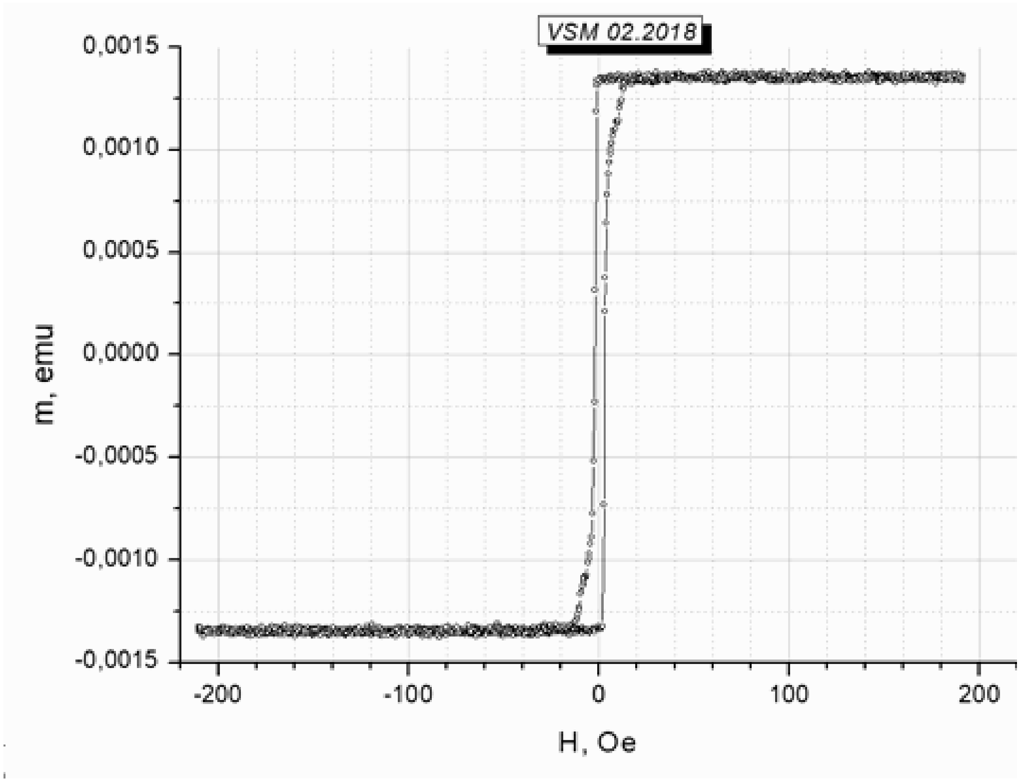
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Fig. 3

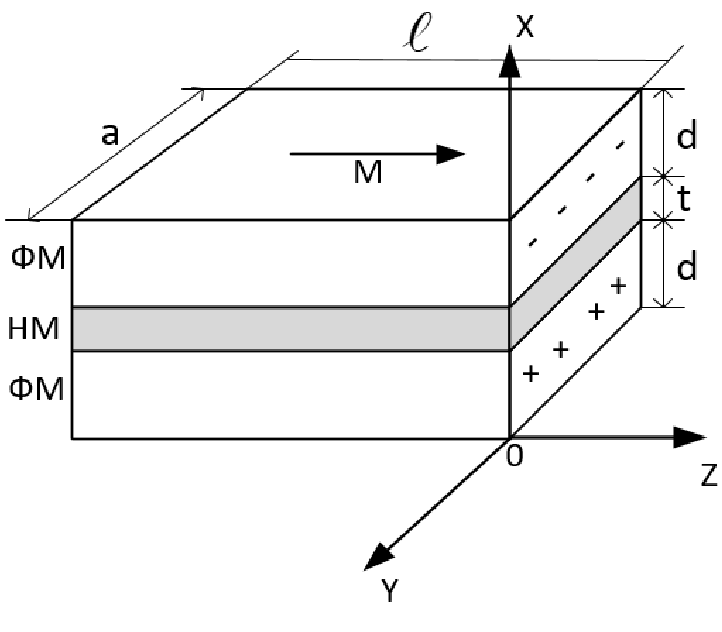
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Fig. 4