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Magnetic anisotropy in Co/Pt films prepared by successive layers deposition of subatomic thicknesses

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The magnetic anisotropy of a thin magnetic film, which favors magnetization to be oriented perpendicular to the film plane, attracts interest as an important component for the realization of non-trivial topological states such as magnetic skyrmions. The paper discusses the results of a study of the magnetic anisotropy in $[Co/Pt]_{10}$ films on Si prepared by successive deposition of Co and Pt layers of subatomic thicknesses. The anisotropy constant and its type (easy axis or easy plane) were estimated using studies of torque, magnetization curves, and ferromagnetic resonance. The patterns of magnetic inhomogeneity calculated using the magnetic anisotropy constant established in the experiment are consistent with the experimental patterns of magnetic force contrast studied earlier. The estimation of the interface magnetic anisotropy constant of the studied Co/Pt films was $k_i = (0.50 \pm 0.17)$ erg/cm^2.

Keywords: magnetic anisotropy, thin films, ferromagnetism.

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1. Introduction

The magnetization of a thin magnetic film in a weak field is significantly smaller in magnitude than the magnetization modulus and is normally in-plane oriented. This pattern is established by the overwhelming contribution of magnetostatic energy, which induces magnetic shape anisotropy with „easy plane" symmetry [1]. A perpendicular magnetic anisotropy constant sufficient to overcome the magnetic shape anisotropy of a film is the cause of „strangeness" of thin magnetic films with their magnetization oriented normally to the surface. Such films based on Co and Pt with a high perpendicular magnetic anisotropy constant attract attention in the context of development of high-density magnetic RAM and non-volatile memory [2,3]. Magnetocrystalline anisotropy (e.g., in epitaxial films containing phases with the $L1_0$ or $L1_1$ structure) or surface and interface anisotropy in thin mono- and multilayer films [4–7] may act as sources of a significant perpendicular magnetic anisotropy in films based on cobalt and platinum. The preparation of Co/Pt films with nanometer-thick layers is regarded as a means to control magnetic properties in general and magnetic anisotropy in particular [8–11]. Multilayer Co/Pt films have also attracted interest due to their strong Dzyaloshinskii–Moriya interface interaction, which provides an opportunity to use them as media for the formation and manipulation of topologically stabilized magnetization configurations (e.g., skyrmions [12–15]). Magnetic anisotropy defined by layer interfaces is very sensitive to the interface structure, mixing at the interface, and internal stresses and, consequently, is governed largely by the specifics of processing of multilayer structures [7,8,16,17]. Therefore, experimental studies into the relation between the fabrication technique, the structure, and the properties of such films remain relevant. In the present study, the magnetic anisotropy constant of $[Co/Pt]_{10}$ films produced by successive deposition of Co and Pt layers of subatomic thicknesses is examined.

2. Experiment

Co/Pt films were formed by electron-beam evaporation in vacuum on Si substrates [12]. Prior to Co/Pt sputtering, an Al_2O_3 layer 1 nm in thickness was deposited onto the surface of samples to prevent Co diffusion into the wafer [18]. Co/Pt layers were grown by successive evaporation of Co and Pt targets by an electron beam under high vacuum ($3 \cdot 10^{-6}$ Torr). The thickness of layers in the multilayer Co/Pt structure was monitored with a weighing piezoelectric cell. The layer thicknesses in a Co/Pt bilayer were set to 0.2–0.5 nm (for Co) and 0.3–0.7 nm (for Pt); the total number of bilayers was 10.

The torque curves were measured using a torsional magnetometer with a sensitivity of $3.76 \cdot 10^{-9}$ N $\cdot$ m in a 10 kOe magnetic field. Ferromagnetic resonance measurements were performed using an ELEXSYS E580 (Bruker) spectrometer with resonator pumping frequency $f = 9.48$ GHz and different orientations of the magnetic field relative to the normal to the film, which are characterized by angle θ. Hysteresis loops were recorded with a vibration magnetometer. The insert with the sample holder was measured separately, and its contribution to the overall signal was subtracted. All measurements were performed at room temperature.

3. Results and discussion

The dependences of torque on the angle of field rotation relative to the film plane provide an opportunity to determine the easy axis direction and obtain a quantitative estimate of the magnetic anisotropy constant.

Angular dependencies were fitted for this purpose with theoretical expressions for torque obtained within the Stoner–Wohlfarth model. The theoretical dependence was calculated from a system composed of equilibrium equations for the magnetization position and the equation for torque $L(H)$ acting on the magnetic moment of a sample in an external field. The model parameters are film magnetization M_s and perpendicular magnetic anisotropy constant K_{op}. The orientation of the field was measured relative to the perpendicular to the wafer (see the inset in Figure 1). According to the Stoner–Wohlfarth model [19], the magnetic energy of the sample in external field H is

$$E(\theta, \phi) = -M_s H \cos(\theta - \phi) - K_p \cos(\phi)^2, \qquad (1)$$

where M_s is the saturation magnetization and K_p is the uniaxial anisotropy constant. In an equilibrium state, $\frac{\partial E}{\partial \phi} = 0$. The angular dependence of torque was calculated as $L = M_s H \sin(\theta - \phi)$, where ϕ was calculated from the equilibrium conditions for parameters M_s, H, θ set in the experiment and K_p. The value of K_p was chosen in such a way as to ensure the closest agreement of this dependence with the experiment.

A similar approach was also used to analyze the angular dependences of ferromagnetic resonance field H_r of films (see, e. g., [20,21]). The selection of a K_p value providing the best agreement with the experimental angular dependence of H_r provided an opportunity to estimate the magnetic anisotropy constant.

Films with the easy axis oriented in-plane and along the normal to the film have qualitatively different angular dependences of the resonance field (Figure 2).

The magnetization curves were measured using a vibration magnetometer with the field applied along and perpendicular to the film plane. The accuracy of measurement of hysteresis loops was low, since the samples were lightweight; however, the difference between magnetization curves is evident and allows one to estimate the anisotropy constant. Figure 3 shows both the sampled points in hysteresis loops, which are characterized by significant noise, and curves representing the averaged magnetization

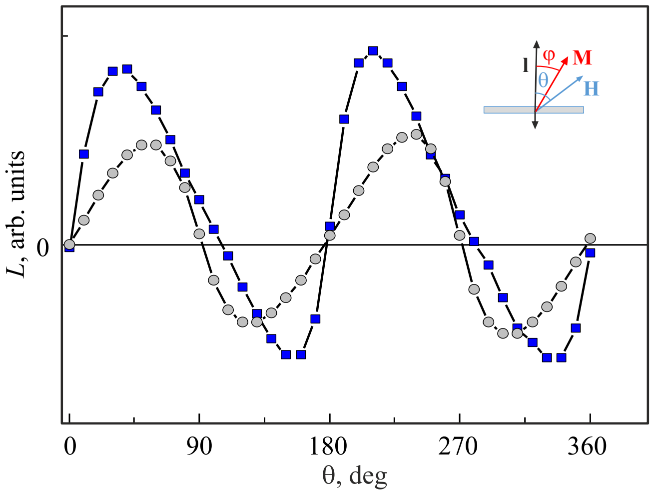

Figure 1. Angular dependences of torque for two samples with anisotropy of the easy axis type oriented perpendicular to the film ($[Co(0.4\,nm)/Pt(0.6\,nm)]_{10}/Al_2O_3(1\,nm)/Si$; squares) and anisotropy of the easy plane type ($[Co(0.4\,nm)/Pt(0.3\,nm)]_{10}/Al_2O_3(1\,nm)/Si$; circles).

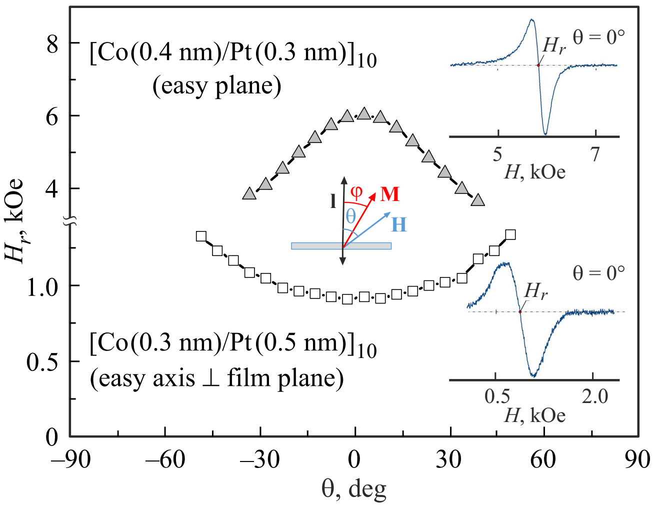

Figure 2. Angular dependences of the resonance field for two films with different signs of effective uniaxial magnetic anisotropy.

changes in a varying field. The anisotropy field estimated from such loops was also used to estimate anisotropy constant $K = H_a M_s/2$ (here, H_a is the magnetic anisotropy field). The sign of this constant depends on the symmetry of magnetic anisotropy: $K > 0$ for „easy axis“ anisotropy (Figure 3, a) and $K < 0$ for „easy plane“ anisotropy (Figure 3, b). Constant $K = K_p - 2\pi M_s^2$. The methods of ferromagnetic resonance and torque measurements allow one to determine the values of perpendicular magnetic anisotropy constant K_p and saturation magnetization M_s separately. The perpendicular magnetic anisotropy constant was estimated in this case as $K_p = K + 2\pi M_s^2$.

A model representation of the film structure is needed to interpret the obtained K_p estimates. Layer-by-layer

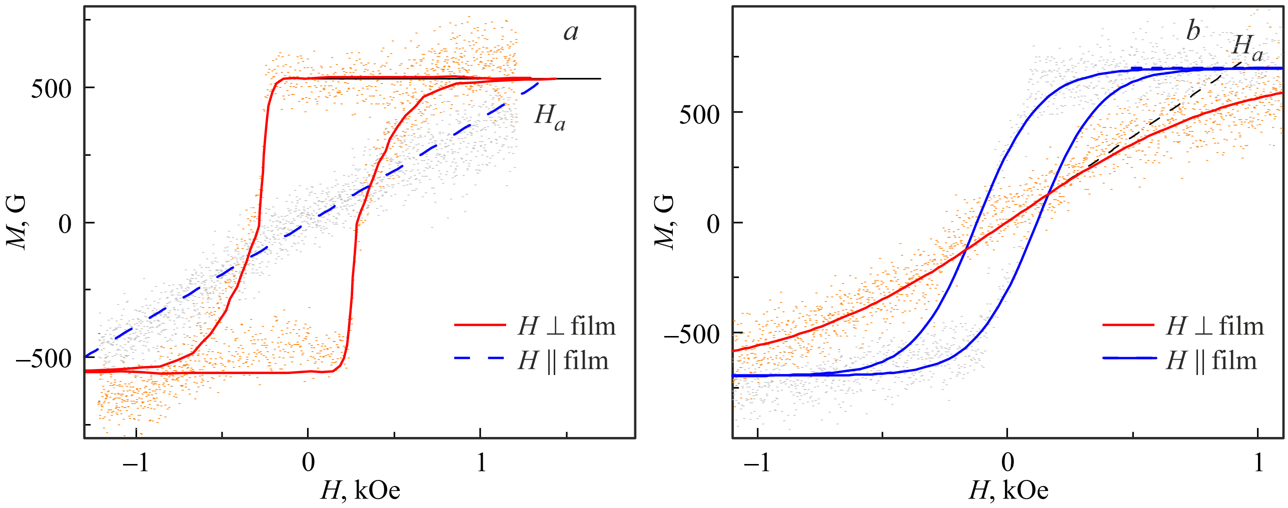

Figure 3. Examples of hysteresis loops corresponding to different orientations of the field relative to the film plane: *a* — $[Co(0.4\,nm)/Pt(0.6\,nm)]_{10}/Al_2O_3(1\,nm)/Si$; *b* — $[Co(0.4\,nm)/Pt(0.3\,nm)]_{10}/Al_2O_3(1\,nm)/Si$.

growth implies the possibility of forming a structure with alternating Co and Pt layers. At the same time, the ultralow layer thickness (on the order of ~ 1 monolayer) makes it doubtful that any compositional modulation in a film is preserved under the conditions of mixing of atoms of adjacent layers. This issue was discussed in [12], and „multilayer“ contrast with a period corresponding to the process procedure was demonstrated in the cross section of a $[Co(0.6\,nm)/Pt(1.0\,nm)]_{10}$ film obtained by electron beam evaporation. Since the films examined in the present study were thinner, it remains unclear whether they had a multilayer structure or a homogeneous structure of a solid solution. Within the context of this dilemma, we examine the behavior of K_p for each model separately.

„Co-Pt alloy film“ model. if complete mixing of atoms of adjacent layers is assumed, the film is a Co-Pt alloy, and the samples differ only in molar fractions of Co and Pt. The data on K_p values for samples with different molar fractions of components are presented in Figure 4.

First, we note that the data obtained using three different methods (torque, magnetization curves, and ferromagnetic resonance) agree within the measurement error. The perpendicular anisotropy constant is maximized in films with a composition close to the equiatomic one (Figure 4). This constant is an order of magnitude lower than the anisotropy constant of the equiatomic ordered CoPt $L1_0$ solid solution. It is fair to assume that the film consists of a disordered Co-Pt solid solution with a certain number of $L1_0$ phase domains oriented perpendicularly to the substrate. The volume fraction of such domains may be estimated at 10% [22–24]. The dashed curve in Figure 4 represents the energy of the magnetic shape anisotropy of the film. It was calculated using the magnetization values of bulk Co-Pt solid solutions [25]. When the $K_p > 2\pi M_s^2$ inequality is fulfilled, the film should be magnetized normally to its plane

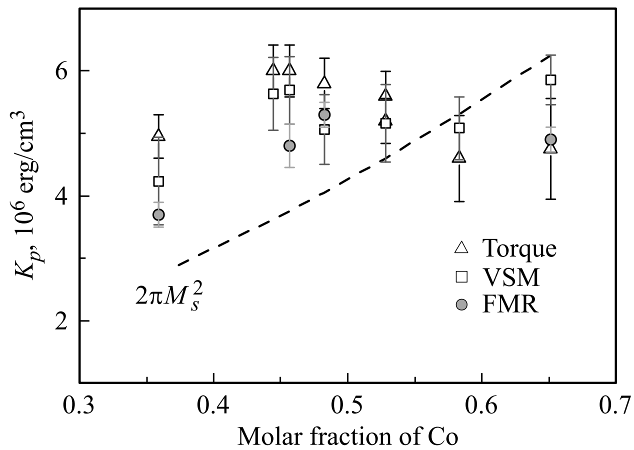

Figure 4. Variation of the anisotropy constant of Co-Pt films with their composition.

in a weak field; in the contrary case, in-plane magnetization should be detected. Notably, this is exactly what is observed for the studied films: two samples with the maximum cobalt content are characterized by magnetic anisotropy of the easy plane type, and an easy axis oriented normally to the film is established in the other films.

„Multilayer Co/Pt film“ model. Having assumed the presence of compositional modulation or interfaces between cobalt and platinum layers, one may analyze the variation of the perpendicular magnetic anisotropy constant with layer thickness. It can be seen from Figure 5, *a* that the Co layer thickness affects the anisotropy constant in four samples with a total Pt thickness of 5 nm and different total Co thicknesses, but the same is not true for samples with a total Co thickness of 4 nm and various total Pt thicknesses.

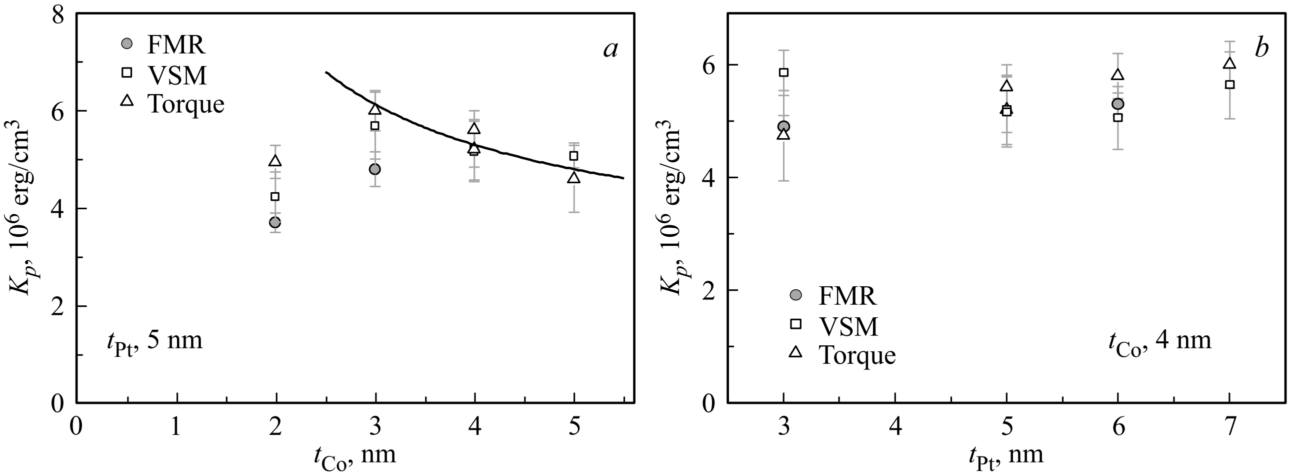

Figure 5. Magnetic anisotropy constant of films: *a* — with a total Pt thickness of 5 nm and different total thicknesses of Co; *b* — with a total Co thickness of 4 nm and different total thicknesses of Pt. The curve in the left panel corresponds to Eq. (2).

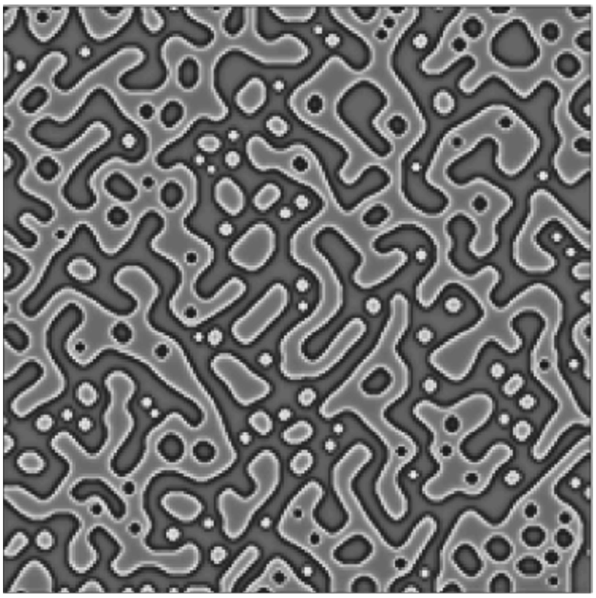

Figure 6. Calculated magnetization divergence in a film with micromagnetic constants corresponding to the studied films. The side of the square is $2\,\mu$m in length.

The influence of ferromagnetic layer thickness t on magnetic anisotropy of the film is typically estimated using the Néel model [4]:

$$K_p = K_{pV} + k_i N/t, \tag{2}$$

where the first term K_{pV} is the bulk anisotropy and the second term is associated with interface anisotropy k_i multiplied by number $k_i N$ of interfaces. Since Co/Pt and Pt/Co interfaces are characterized by a strong spin-orbit interaction and a large number of such interfaces are present in the examined samples, one may assume that these interfaces produce an overwhelming contribution to interface anisotropy, ignore the Co/substrate interface anisotropy, and set $N = 19$. Equation (2) characterizes the anisotropy of three samples with a total cobalt thickness of 3, 4, and 5 nm well, while the sample with a thickness of 2 nm deviates noticeably from the curve corresponding to Eq. (2). The observed deviation may be attributed to the formation of an alloy in this sample. This distinguishes it from films with thicker layers that tend to form a laminar structure in the film. The magnetic anisotropy constants corresponding to the curve in Figure 5, *a* are $K_{pV} = (2.8 \pm 0.8) \cdot 10^6$ erg/cm^3 and $k_i = (0.50 \pm 0.17)$ erg/cm^2 and agree closely with the constants determined earlier for multilayer Co/Pt films with comparable layer thicknesses [5,8,10,11,26].

The estimated micromagnetic constants were used for micromagnetic modeling of films in the OOMMF [27] software package. The values of constants close to the constants of these films were set in modeling: exchange constant $A = 0.7 \cdot 10^{-6}$ erg/cm [28]; magnetization $M_s = 800$ G; the chosen value of Dzyaloshinskii–Moriya constant $D = 0.6$ erg/cm^2 was similar to the ones from [12,29]; magnetic anisotropy constant $K = 6 \cdot 10^6$ erg/cm^3 was set to be close to the values measured in the present study; and the easy axis was perpendicular to the film plane.

The result of calculations of equilibrium magnetization for a 5-nm-thick film is presented in Figure 6. This figure illustrates the magnitude of magnetization divergence (related directly to the images obtained with a magnetic force microscope (MFM)). The magnetization of light and dark domains is perpendicular to the image plane. The obtained pattern is qualitatively similar to the MFM patterns recorded earlier for these films [12]. Since domain sizes and the domain structure type are sensitive to both the specific set of constants and the magnetic history of the film, the similarity between Figure 6 and experimentally observed MFM patterns may be regarded as a verification of reliability of the measured data on magnetic constants.

4. Conclusion

The magnetic anisotropy constant of $[\mathrm{Co/Pt}]_{10}$ films on a Si substrate prepared by successive deposition of Co with an effective thickness of 0.2–0.5 nm and Pt (0.3–0.7 nm) was studied. The methods used (examination of torque, magnetization curves, and ferromagnetic resonance) allowed us to estimate the anisotropy constant and its type (easy axis or easy plane) and revealed that the estimates agreed within the measurement errors. Competition between the perpendicular magnetic anisotropy constant and magnetic shape anisotropy governs the magnetization of the studied samples, which is oriented either perpendicular to the film plane or in-plane. The use of the experimentally determined magnetic anisotropy constant in micromagnetic modeling helped obtain calculated micromagnetic patterns consistent with those examined earlier in experiments. The magnetic anisotropy constant reaches its maximum in films with a composition close to the equiatomic one, but is significantly lower than the anisotropy constant of the equiatomic ordered CoPt $L1_0$ solid solution. The analysis of variation of the anisotropy constant with effective thickness of the cobalt layer at a constant thickness of the platinum layer provided an opportunity to estimate the interface anisotropy of Co/Pt as $k_i = (0.50 \pm 0.17)\,\mathrm{erg/cm^2}$, which is consistent with the data obtained earlier by other research groups.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] N.M. Salanskii, M.Sh. Erukhimov. Fizicheskie svoistva i primenenie magnitnykh plenok. Nauka, Novosibirsk (1975). (in Russian).
[2] J. Ariake, T. Chiba, S. Watanabe, N. Honda, K. Ouchi. J. Magn. Magn. Mater. **287**, 229 (2005).
[3] Y. Kawada, Y. Ueno, K. Shibata. IEEE Trans. Magn. **38**, 2045 (2002).
[4] L. Néel. J. Phys. Le Radium. **15**, 225 (1954).
[5] D. Weiler, R.F.C. Farrow, R.F. Marks, G.R. Harp, H. Notarys, G. Gorman. MRS Proc. **313**, 791 (1993).
[6] N. Nozawa, S. Saito, S. Hinata, M. Takahashi. J. Phys. D **46**, 172001 (2013).
[7] Y.C. Won, S.H. Lim. Sci. Rep. **11**, 10779 (2021).
[8] T.Y. Lee, Y. Chan Won, D. Su Son, S. Ho Lim, S.-R. Lee. J. Appl. Phys. **114**, 173909 (2013).
[9] K. Yakushiji, T. Saruya, H. Kubota, A. Fukushima, T. Nagahama, S. Yuasa, K. Ando. Appl. Phys. Lett. **97**, 232508 (2010).
[10] T. Young Lee, D. Su Son, S. Ho Lim, S.-R. Lee. J. Appl. Phys. **113**, 216102 (2013).
[11] I.B. Chung, Y.M. Koo, J.M. Lee. J. Appl. Phys. **87**, 4205 (2000).
[12] M.V. Dorokhin, A.V. Zdoroveyshchev, M.P. Temiryazeva, A.G. Temiryazev, P.B. Demina, O.V. Vikhrova, A.V. Kudrin, I.L. Kalentyeva, M.V. Ved, A.N. Orlova, V.N. Trushin, A.V. Sadovnikov, D.A. Tatarskiy. J. Alloys Compd. **926**, 166956 (2022).
[13] Y. Zhou, R. Mansell, S. van Dijken. Appl. Phys. Lett. **118**, 172409 (2021).
[14] H. Yang, A. Thiaville, S. Rohart, A. Fert, M. Chshiev. Phys. Rev. Lett. **115**, 267210 (2015).
[15] L. Wang, C. Liu, N. Mehmood, G. Han, Y. Wang, X. Xu, C. Feng, Z. Hou, Y. Peng, X. Gao, G. Yu. ACS Appl. Mater. Interfaces. **11**, 12098 (2019).
[16] S. Bandiera, R.R. Sousa, B.B. Rodmacq, B. Dieny. IEEE Magn. Lett. **2**, 3000504 (2011).
[17] D. Ourdani, Y. Roussigné, S.M. Chérif, M.S. Gabor, M. Belmeguenai. J. Phys. D **55**, 485004 (2022).
[18] A.I. Bobrov, Y.A. Danilov, M.V. Dorokhin, A.V. Zdoroveyshchev, N.V. Malekhonova, E.I. Malysheva, D.A. Pavlov, S. Saeid. J. Surf. Investig. X-Ray, Synchrotron Neutron Tech. **9**, 706 (2015).
[19] E.C. Stoner, E.P. Wohlfarth. Phil. Trans. Roy. Soc. A **240**, 559 (1948).
[20] G.Y. Melnikov, I.G. Vazhenina, R.S. Iskhakov, N.M. Boev, S.V. Komogortsev, A.V. Svalov, G.V. Kurlyandskaya. Sensors **23**, 6165 (2023).
[21] S.V. Komogortsev, I.G. Vazhenina, S.A. Kleshnina, R.S. Iskhakov, V.N. Lepalovskij, A.A. Pasynkova, A.V. Svalov. Sensors **22**, 3324 (2022).
[22] P.D. Kim, I.A. Turpanov, S.V. Stolyar, R.S. Iskhakov, V.I. Yushkov, A.Y. Beten'kova, L.A. Li, E.V. Bondareva, T.N. Isaeva, M.M. Karpenko. Tech. Phys. **49**, 431 (2004).
[23] P.D. Kim, I.A. Turpanov, S.V. Stolyar, V.I. Yushkov, D.L. Khalyapin. Phys. Met. Metallogr. **102**, S83 (2006).
[24] S.V. Komogortsev, R.S. Iskhakov, A.A. Zimin, E.Y. Filatov, S.V. Korenev, Y.V. Shubin, N.A. Chizhik, G.Y. Yurkin, E.V. Eremin. Appl. Phys. Lett. **103**, 152404 (2013).
[25] S. Jen, T. Chen, B. Chao. Phys. Rev. B **48**, 12789 (1993).
[26] F.J.A. den Broeder, W. Hoving, P.J.H. Bloemen. J. Magn. Magn. Mater. **93**, 562 (1991).
[27] M.J. Donahue, D.G. Porter. OOMMF user's guide, version 1.0. MD, Gaithersburg (1999).
[28] S.V. Komogortsev, R.S. Iskhakov, A.A. Zimin, E.Y. Filatov, S.V. Korenev, Y.V. Shubin, N.A. Chizhik, G.Y. Yurkin, E.V. Eremin. J. Magn. Magn. Mater. **401**, 236 (2016).
[29] I.L. Kalentyeva, O.V. Vikhrova, Yu.A. Danilov, A.V. Zdoroveyshchev, M.V. Dorokhin, Yu.A. Dudin, A.V. Kudrin, M.P. Temiryazeva, A.G. Temiryazev, S.A. Nikitov, A.V. Sadovnikov. Phys. Solid State **63**, 386 (2021).

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