

## A method for studying magneto-optical characteristics of individual magnetic layers of a three-layer system

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Contributions from different individual cobalt layers have been identified in the integral magneto-optical response of three-layer magnetic structure Co(6 nm)/Ru(10 nm)/Co(10 nm)/Si(100). A method has been developed and presented that makes it possible to describe, based on analyzing the patterns of magneto-optical dependencies, magnetic properties of individual magnetic layers of three-layer systems. The developed method allows establishing the directions of magnetic anisotropy in every magnetic system layer.

**Keywords:** magnetic properties, multilayer structures, magneto-optical Kerr effect, magnetic anisotropy, interface.

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Research works in the field of using multilayer magnetic systems for magnetic recording of information has been going on for quite a long time. A review of previous studies in this field is given in [1]. This paper presents the data on using the magneto-optical Kerr effect in multilayer dielectric systems comprising a magnetic layer. The method of writing and reading the signal by using this effect in multilayer systems based on TbFe/SiO layers was implemented in [2]. Theoretical developments in the field of spin reorientation in multilayer systems with antiferromagnetic coupling are presented in [3]. Paper [4] presents the calculations of the electric field distribution in multilayer systems containing a magnetic layer. Specific features of signals from multilayer magnetic systems Au(5nm)/Co(1.2nm)/Au(3nm)/Co(0.8nm)/Au(25nm) and (TbFe/Si<sub>3</sub>N<sub>4</sub>)<sub>4</sub> were studied in [5]. Properties of magnetic multilayer systems Gd<sub>x</sub>FeCo/SiN/Gd<sub>y</sub>FeCo were studied in detail in [6] where was also indicated a way for separating signals from different magnetic layers through examining features of the magneto-optical response signal. Such a response in multilayer systems was comprehensively studied in [7,8] where theoretical and technological aspects of functioning of multilayer magnetic systems were considered. A review of the magneto-optical properties of multilayer systems is also given in [9]; this paper emphasizes the importance for such structures of accounting for the interface processes and describes phenomena occurring at the boundaries of non-magnetic and magnetic media. Note that the mentioned papers do not present the results of studying the multilayer system magnetic anisotropy, which might be achieved using the method proposed in this study. The proposed method enables investigation of features introduced by relevant interfaces into the magnetization distribution in the multilayer structure thin films.

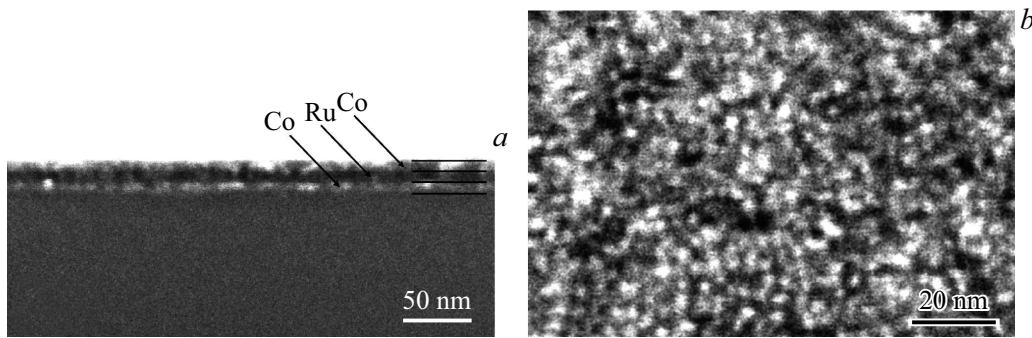
In this paper we propose a method for studying the anisotropy of magnetic properties of individual layers in a three-layer structure consisting of two magnetic layers separated by a buffer layer. This method is based on using the magneto-optical equatorial Kerr effect (MOEKE) and may be generalized to more complex systems, since the depth of the informative MOEKE signal can reach 80 nm [10].

Metal films were deposited on Si(100) wafers coated with natural oxide by using magnetron sputtering setup SCR-651 Tetra (Alcatel). The Co and Ru targets 99.95 % pure were sputtered by Ar 99.995 % pure; the Ar operating pressure was 0.2 Pa. The residual pressure was  $5 \cdot 10^{-5}$  Pa, high-frequency power on the target was 300 W.

In this work, we examined hysteresis loops measured in an alternating magnetic field using MOEKE. The measurements were performed at room temperature under the procedure described in detail in [11]. The sample was placed between the poles of electromagnet creating a magnetic field with the frequency of 30 Hz and amplitude of up to 1000 Oe sufficient for magnetic saturation of the sample [11]. A 1-mm-dia light laser beam polarized in the plane of incidence (*p*-wave) was reflected from the film surface in a standard configuration for MOEKE measurements; the magnetic field direction was perpendicular to the plane of laser beam incidence. The measurements were performed at different beam incidence angles  $\varphi$ . The quantity to be measured was

$$\delta = \Delta I / I(0), \quad (1)$$

Here  $I(H)$  is the intensity of light reflected from the magnetized surface,  $I(0)$  is the intensity of light reflected from the non-magnetized surface, and  $H$  is the magnetic field magnitude. The  $\Delta I$  value is proportional to the alternating component of the photodetector current,  $I(0)$  is proportional to the direct component of the current.



**Figure 1.** *a* — SEM image of the Co(6 nm)/Ru(10 nm)/Co(10 nm)/Si structure transverse cleavage (cross-section). *b* — SEM image of the top cobalt film surface in the structure under study.

The  $\delta$  dependence on magnetic field  $\delta(H)$  had a form of a magneto-optical hysteresis loop (MOHL). The MOEKE amplitude was defined as  $\delta_m = \delta(H_m)$ , where  $H_m$  is the field strength amplitude. The laser radiation wavelength was  $\lambda = 633$  nm. The image of the Si(220) pole figure fragment was obtained with diffractometer DRON-3M using the  $\text{CuK}\alpha$  radiation at sample tilt angles  $\psi = 39\text{--}49^\circ$ . The system's surface and transverse cleavage morphology was examined using scanning electron microscope (SEM) Supra-40 (Carl Zeiss). Film thicknesses were determined from SEM images of the cleavages.

Fig. 1, *a* presents SEM images of the structure under study. As per the results of SEM studies, thicknesses of the top and bottom Co films are 6 and 10 nm, respectively, while the Ru film thickness is 10 nm. The cobalt films were polycrystalline layers with the lateral crystallite size of about 5 nm (Fig. 1, *b*).

At the first stage of research there was measured the response in the MOEKE configuration for two— and single-layer test structures on Si(100) with the thicknesses and boundaries corresponding to the studied three-layer magnetic structure, namely for the Co(6 nm)/Ru(10 nm)/Si(100) and Co(10 nm)/Si(100) films. Fig. 2, *a* shows angular dependences  $\delta_m(\varphi)$  which indicate that the magneto-optical response from these structures is zero at different beam incidence angles at which inversion of MOHL takes place. For instance, when the incidence angle is  $76^\circ$ , the response from the Co/Si system is zero.

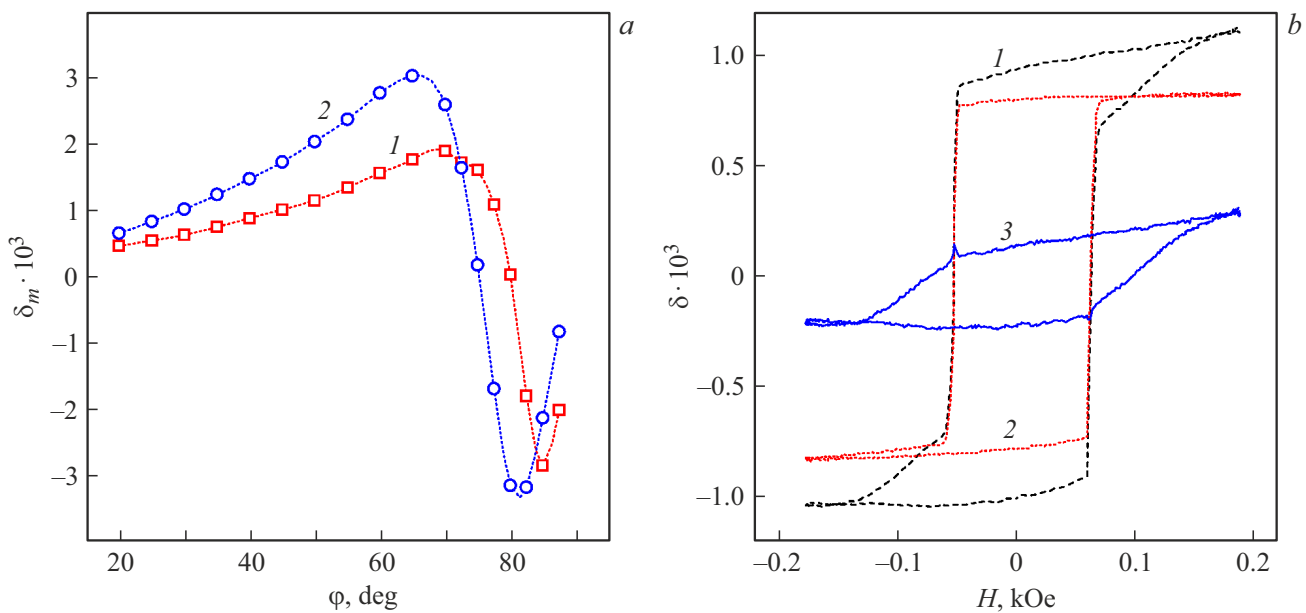
Fig. 2, *b* presents hysteresis loops for the studied three-layer system at two different angles of incidence. As per Fig. 2, *a*, at the light incidence angle of  $76^\circ$ , the magneto-optical response from the bottom Co/Si layer is zero; therefore, the magneto-optical response at the beam incidence angle of  $76^\circ$  is determined by the Co/Ru layer of the three-layer Co/Ru/Co/Si system. Since the hysteresis loop measured at  $\varphi = 45^\circ$  is a superposition of two loops corresponding to the Co (6 nm) and Co (10 nm) ferromagnetic layers, the Co (10 nm) layer hysteresis loop should be obtained by subtracting the loop measured at  $\varphi = 76^\circ$  from the loop measured at  $\varphi = 45^\circ$ . As shown in Fig. 2, *a*,  $\delta_m$  of the Co/Ru film at  $\varphi = 45^\circ$  is less than

$\delta_m$  at  $\varphi = 76^\circ$ . Therefore, in subtraction it is necessary to multiply the values for hysteresis loop measured at  $\varphi = 76^\circ$  by an empirical coefficient accounting for this difference. The correctness criterion for selecting this coefficient was the absence of discontinuities in the formed hysteresis loop (Fig. 2, *b*); in our case it is  $k = 0.63$ . Thus, the MOHL linear transformation is performed, which may be conditionally defined as follows:

$$\mathbb{R}^2 \rightarrow \mathbb{R}^2, T(C_1\mathbf{V}_1 + C_2\mathbf{V}_2) = C_1T(\mathbf{V}_1) + C_2T(\mathbf{V}_2), \quad (2)$$

where  $\mathbb{R}^2$  is the space of two-dimensional real numbers,  $T(\mathbf{V})$  is the linear transformation of the space elements,  $C_1, C_2$  are the numerical coefficients (in our case,  $C_1 = 1, C_2 = k$ ),  $\mathbf{V}_1$  is the horizontal component,  $\mathbf{V}_2$  is the vertical component.

Paper [12] shows that the hysteresis loop shape for the structures with one magnetic layer does not change with the beam incidence angle. In the structures with several magnetic layers, the loop shape changes with the beam incidence angle [12]. This is because at different incidence angles the electromagnetic radiation interacts with different magnetic layers [12]. Fig. 2, *b* shows that the loop shape for the Co/Ru/Co/Si multilayer structure varies with varying incidence angle. Shapes of hysteresis loops 1 and 2 presented in Fig. 2, *b* are different. As shown in Fig. 2, *b*, hysteresis loop 2 is typical for the easy magnetization axis (beam incidence angle is  $\varphi = 76^\circ$ ). The easy magnetization axis is observed in this direction only for the top layer (Fig. 2, *b*, axis EA Co/Ru). In the bottom layer, in this direction there is a hard magnetization axis (Fig. 2, *b*, axis HA-2 Co/Si). Hence, in the case of the beam incidence angle  $\varphi = 76^\circ$  when, as per Fig. 2, *a*, the response from the bottom layer is zero, the contribution is made only by top layer Co/Ru that exhibits in this direction the easy magnetization axis, and there is no magneto-optical response from the bottom layer. At the incidence angle of  $45^\circ$ , both layers contribute to the resulting MOHL; this is manifested by hysteresis loop 1 in Fig. 2, *b*, which does not match MOHL for the easy magnetization axis. This fact clearly illustrates the statement made about the absence of a contribution from the bottom Co layer at



**Figure 2.** *a* —  $\delta_m$  dependences on light incidence angle  $\varphi$  for the Co(6 nm)/Ru(10 nm)/Si (1) and Co(10 nm)/Si (2) films. *b* — hysteresis loops of the Co(6 nm)/Ru(10 nm)/Co(10 nm)/Si sample and its individual layers for light incidence angles  $\varphi = 45^\circ$  (1) and  $76^\circ$  (2). 3 — the difference in hysteresis loops corresponding to the bottom Co(10 nm)/Si layer in a three-layer structure on a silicon substrate; the sample orientation is  $\theta = 0^\circ$ ,  $k = 0.63$ .

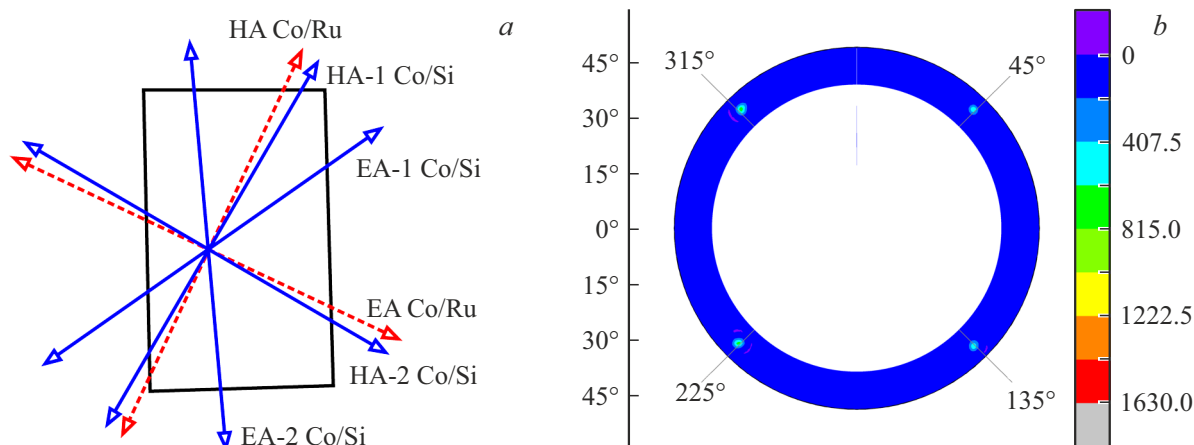
the incidence angle at which MOHL gets inverted. The incidence angle is set to  $45^\circ$  quite arbitrarily, based on the condition of precise fixation of MOHL, which is not met at small incidence angles and angles close to grazing.

The criterion of the hysteresis loop smoothness seems reasonable in view of the fact that the resulting response of our system at the incident radiation wavelength  $\lambda = 633$  nm and of the Co/Ru/Co/Si system was characterized by a smooth hysteresis loop in all the situations we studied; when a loop from any layer has a discontinuity, the loop from another layer should have exactly compensated this discontinuity. Besides this, the additionally studied Co/Ru/Si and Co/Si structures constituting the studied system were also characterized by continuous MOHLs in all cases, although they had interfaces with materials with different properties. Note that for other wavelengths, e.g. in the (TbFe/Si<sub>3</sub>N<sub>4</sub>)<sub>4</sub> system [5], discontinuous hysteresis loops were also observed in the polar magneto-optical Kerr effect. Such situations need more investigation.

MOHL were measured at different angles  $\theta$  of the sample rotation in its own plane. Angle  $\theta$  was varied within the range of 0 to  $350^\circ$  with the step of 5 to  $10^\circ$ ; therefore, the error was about  $5^\circ$ . Reducing the step of recording the results provides improvement of the method accuracy. Reference angle  $\theta = 0^\circ$  was conditionally assumed to be the angle between the easiest magnetization axis for the top Co/Ru layer of the three-layer structure under study (Fig. 3, *a*, dashed

line EA Co/Ru). The research results are presented in Fig. 3, *a*. Those results show that the top Co/Ru layer of the studied three-layer structure has one conditional axis of the easiest magnetization and one of the hardest magnetization. Term „conditional axis of hard/easy magnetization“ is used because the respective hysteresis loops are somewhat different from the canonical loops and do not reach saturation; therefore, we used as a criterion the fact that, during remagnetization along the easy magnetization axis, the hysteresis loop shape was almost rectangular, whereas during remagnetization along the hard magnetization axis no rectangularity was observed. However, the constructed polar diagrams of the coercive force and residual magnetization dependences on the angle of the sample rotation in its plane make it possible to identify the directions of the easiest/hardest magnetization. The bottom layer (Co/Si) of the studied three-dimensional structure has two mutually orthogonal hardest magnetization axes and two easy magnetization axes that are not orthogonal to each other. The pole figure in Fig. 3, *b* determines the position of crystallographic axes of the silicon(100) substrate. Based on this pole figure, we may state that the sample sides are oriented along crystallographic directions  $\langle 110 \rangle$  of the silicon(100) substrate.

The proposed method may be useful for the diagnostics of three-dimensional functional electronic systems, e.g. memory, with different magnetic states in each magnetic layer.



**Figure 3.** *a* — orientation of conditional easy magnetization (EA) and hard magnetization (HA) axes in the three-layer Co/Ru/Co/Si structure. The dashed lines represent the axes of the top magnetic layer Co/Ru, solid lines indicate those of the bottom layer Co/Si, and the rectangle indicates the position of the sample with the structure. *b* — fragment of the pole figure  $39 \leq \psi \leq 49^\circ$  Si (220) for the sample under study. Positions of the maxima indicate that four  $\langle 110 \rangle$  directions are oriented along the sample sides.

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## Conflict of interests

The authors declare that they have no conflict of interests.

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