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Magneto-Optical Study of NiFe/Au/Co/Au Layers

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Sputtered NiFe/Au/Co/Au layers with noncollinear magnetizations are of scientific interest for unusual magnetization behavior and their potential application in spintronics. In this paper, we propose to use a material selective sensitivity of magneto-optical Kerr effect for separation of signals from different materials in a bilayer system. The materials selective sensitivity is demonstrated on a sample with two mutually perpendicular Co and NiFe wedges.

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1. Introduction

Magnetic thin films reveal a broad range of magnetic properties which depend on thickness and growth conditions [1]. The magnetic properties can be measured using various techniques but one of the most popular is magnetometry based on magneto-optical (MO) effects. MO effects are very often applied to study thin-film magnetic phenomena such as magnetization reversal, anisotropy, interlayer coupling, and magnetization dynamics [2]. MO techniques are very useful because of their high near-surface sensitivity and nondestructive character, and they also give the possibility to measure all components of the magnetization vector in the frame of magneto-optic vector magnetometry [3, 4]. The depth sensitivity of MO effects has been systematically studied by Traeger et al. [5] and Hubert and Traeger [6] using modeling of the MO effects from a buried thin magnetic film in a non-magnetic surrounding. The separation of polar MO signal from films of different depths was presented by Ferre et al. [7] and Hamrle et al. [8, 9] in the case of Co films separated by Au spacer. The depth sensitivity of the longitudinal Kerr effect in Fe/Cr/Fe structure was demonstrated by Nyvlt et al. [10].

In this paper we demonstrate a materials selective sensitivity of MO effects in the case of NiFe/ Au/ Co/ Au bilayers.

2. Experimental details

The sputtered [NiFe/Au/Co/Au] (NiFe = $Ni_{80}Fe_{20}$ = Py — permalloy) layers with mutually perpendicular wedges of Co and NiFe were prepared by dc (Co, Py) and rf (Au) magnetron sputtering in UHV conditions on oxidized silicon substrates (14 × 19 mm) covered by a 2 nm thick Au buffer layer. Then the following structures were grown (see Fig. 1): (i) the Co wedge changes thickness d from 0 at $x = 2$ mm to 1.7 nm at $x = 9$ mm, and above this coordinate is constant; (ii) the thickness of the Py wedge increases along the y-axis from 0 at $y = 7$ mm to 2 nm at $y = 15$ mm, and above this coordinate is constant. The wedges were separated by a 2 nm thick Au layer; a layer of the same thickness was used to cover the sample to prevent oxidation. Measurements were performed at room temperature using classical MO magnetometer and optical microscope, both based on the polar Kerr effect as a function of magnetic field H applied perpendicular to the sample surface. During measurements with MO magnetometer and optical microscope, we used a laser light wavelength of 640 nm and spot diameter of 0.5 mm and light from a xenon lamp, respectively. The LabView program controls both measurements.

3. Theoretical background

Information about magnetization included in the MO Kerr effect can be detected either using Kerr rotation θ_K or Kerr ellipticity ϵ_K. Both of them are represented by the complex MO Kerr effect $\phi_K = \theta_K + i\,\epsilon_K$. Different azimuth angles among contribution from particular layers in the complex MO plane give the possibility for separation of MO signals from Co and NiFe films. From literature a few methods for separation MO signals are known:

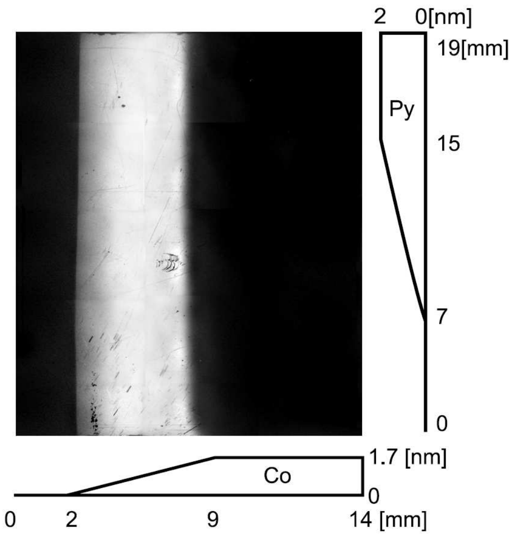

Fig. 1. Image of remanent magnetization state of the sample with two mutually perpendicular wedges of Co and NiFe.

(i) adjustment of the wavelength of the inspecting optical beam [7], (ii) phase adjustment of magneto-optic ellipsometer using a Babinet–Soleil compensator [7, 8], and (iii) a numerical analysis of linear combination of measured Kerr rotation and ellipticity. Here we demonstrate separation of the Co and NiFe contributions by a linear combination of measured Kerr rotation and Kerr ellipticity. The measured polar MO Kerr rotation and ellipticity can be written as weighted sums

$$\theta = a_1 m_1 + a_2 m_2 \,, \tag{1}$$

$$\epsilon = b_1 m_1 + b_2 m_2 \,, \tag{2}$$

where $a_{1,2}$ and $b_{1,2}$ are weight coefficients, and m_1 and m_2 are the polar magnetization components relative to the saturated magnetization m_S of the Co and NiFe layers, respectively. It is possible to write Eqs. (1) and (2) using the matrix form

$$\Phi = \begin{bmatrix} \theta \\ \epsilon \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \boldsymbol{A}\boldsymbol{M}. \tag{3}$$

If we know the coefficients $a_{1,2}$ and $b_{1,2}$, we can obtain the magnetization of Co and NiFe using the matrix inversion [11]:

$$\boldsymbol{M} = \boldsymbol{A}^{-1}\Phi \,. \tag{4}$$

4. Experimental results

The perpendicular easy-axis-state region, located in the left part of the sample, is imaged as a bright area in Fig. 1, because of high remanent magnetization related to square hysteresis loops. The brightness increases from the left to the right due to an increase in the maximal Kerr rotation with the increase in cobalt thickness d.

The left-hand-side dark area in Fig. 1 corresponds to either a superparamagnetic or ferromagnetic state with negligible remanence. Meanwhile, the right-hand-side dark area corresponds to the in-plane magnetization state. Hysteresis loops measured by MO polar Kerr rotation and ellipticity differ significantly, not only in maximal effect but also in their shape. Figure 2 shows an example of measured hysteresis loops for $d_{\mathrm{Co}} = 0.8$ nm and $d_{\mathrm{NiFe}} = 2$ nm.

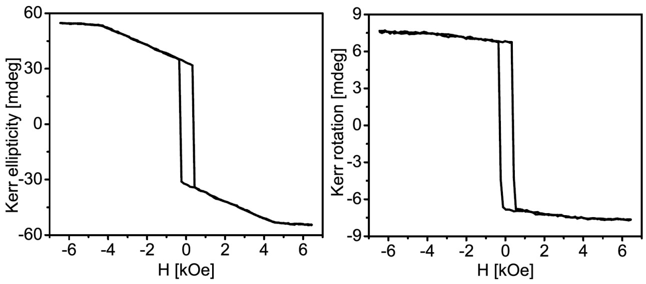

Fig. 2. Kerr rotation and ellipticity measurements for $d_{\mathrm{Co}} = 0.8$ nm and $d_{\mathrm{NiFe}} = 2$ nm.

Similar differences were obtained for various thicknesses of NiFe and Co films. Contribution of Co dominates for the loops of the Kerr rotation. However, the Kerr ellipticity clearly shows both Co and NiFe contributions. Contribution from NiFe in the Kerr rotation is visible only for the thickest part of the NiFe wedge.

Using this difference it is possible to separate the contributions of Co and NiFe from the hysteresis loops. On the basis of hysteresis loops similar to those discussed above, we determined (i) the total saturated signals $\theta_{\max}$ and $\epsilon_{\max}$ originating from Co and NiFe films magnetized in a perpendicular direction for the magnetic field higher than 5 kOe and (ii) remanence-like effects obtained by linear extrapolation of the inclined straight part of the hysteresis loop for a magnetic field in the range 0–3(5) kOe depending on Co and NiFe films thickness. These values are denoted as θ_1 and ϵ_1. Our expectation is that hysteresis loop in this range comes from NiFe films in their monodomain state [12]. The Co and NiFe films without domain structures are not coupled to each other by magnetostatic interaction [12, 13]. We expect that the Co film is saturated in a perpendicular direction everywhere except for small values of magnetic field (i.e., in the hysteretic range). Using this approximation our θ_1 and ϵ_1 represent the MO contributions of Co film; then matrix $\boldsymbol{A}$ has the form

$$\boldsymbol{A} = \begin{bmatrix} \theta_1 & \theta_{\max} - \theta_1 \\ \epsilon_1 & \epsilon_{\max} - \epsilon_1 \end{bmatrix}. \tag{5}$$

Using Eq. (4) it is possible to obtain separated magnetization loops for Co and NiFe films. The example of separated loops from Fig. 2 is shown in Fig. 3.

It is seen that Co has a square hysteresis loop and for a higher magnetic field, it is fully saturated as we expected from our assumption. Meanwhile, on the separated NiFe loop, the rotational behavior of magnetization is clearly visible. Similar behavior of separated loops was observed

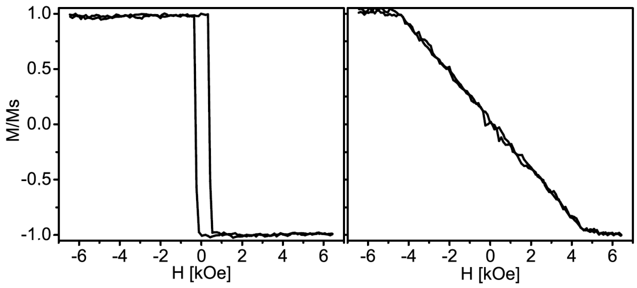

Fig. 3. Separated MO contribution of Co and NiFe films for the sample with $d_{\mathrm{Co}} = 0.8$ nm and $d_{\mathrm{NiFe}} = 2$ nm.

for all hysteresis with some squareness of the hysteresis loop independent of the thickness of the Co and NiFe films.

5. Conclusion

In this paper we have shown an example of the material selectivity of the magneto-optical Kerr effect and a mathematical model which enables the separation of the contributions of Co and NiFe films from hysteresis loops of the multilayer.

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