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Magnetic properties of (Co/Au)$_N$ multilayers with various numbers of repetition N[*]

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Magnetization reversal processes and magnetic domain structures have been studied in multilayered systems consisting of magnetostatically coupled cobalt layers separated by non-magnetic/soft-magnetic ones. Observations of the domain structures have been performed at room temperature using Kerr microscopy and magnetic force microscopy technique. The studies have been focused on the key characteristics of magnetic hysteresis loops as well as the domain structures and domain periods in such systems.

Key words: multilayers; ultrathin film; cobalt; domain structure; hysteresis loop

1. Introduction

Magnetic multilayers have been the subject of intensive research. Interest in such systems has grown rapidly, being motivated by the search of new magnetic materials, their novel magnetic properties and applications. Properties of magnetic multilayers can be easily manipulated by varying the thickness of both the magnetic and non-magnetic layers as well as by varying the number of layers [1–3]. It is known that in magnetic multilayers with perpendicular anisotropy, the saturation field of stripe domains exhibits a non-trivial dependence on the thickness of non-magnetic spacing [4]. Influence of ultrathin film thickness on the size of domain structure has been recently described [5].

In the paper, the influence of Co and Au layer thicknesses as well as the number of repetitions N on the magnetic properties of Co/Au multilayers has been presented.

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2. Samples and experiment

A few series of $[\mathrm{Co/Au}]_N$ and $[\mathrm{Py/Au/Co/Au}]_N$ (Py = $\mathrm{Ni_{80}Fe_{20}}$) magnetic multilayers were deposited by dc magnetron sputtering in UHV conditions on an oxidized silicon substrate with the following structure:

- buffers – either Au (5 nm) or $[\mathrm{Py}\ (2\ \mathrm{nm})/\mathrm{Au}\ (2\ \mathrm{nm})]_{10}$,
- multilayers – either $[\mathrm{Co}\ (d_{\mathrm{Co}})/\mathrm{Au}\ (d_{\mathrm{Au}})]_N$ or $[\mathrm{Py}\ (2\ \mathrm{nm})/\mathrm{Au}\ (d_{\mathrm{Au}})/\mathrm{Co}\ (d_{\mathrm{Co}})/\mathrm{Au}\ (d_{\mathrm{Au}})]_N$, with $d_{\mathrm{Co}} = 0.6$–1.5 nm, $d_{\mathrm{Au}} = 1.5$ nm, 3 nm, and $N = 1$–15.

Sample composition was controlled by the XRF technique. Such specific types of structures were produced in order to examine the influence of magnetic (Co), non-magnetic (Au) and soft magnetic (Py) layers on the magnetic properties of nanostructures and their domain structures. All magnetic measurements in multilayer samples were done ex-situ at room temperature using the following techniques: magneto-optical Kerr effect (MOKE) for magnetic domain structure visualization, magneto-optical millimagnetometry for recording hysteresis curves as a function of magnetic field applied perpendicularly to the sample plane and atomic and magnetic force microscopy (AFM/MFM) for both surface structure and magnetic domain structure imaging beyond the optical resolution. The study of magnetization reversal was performed using a MOKE-based magnetometer with the laser wavelength of 640 nm and a spot diameter of 0.5 mm. The polar magnetization component was measured as a function of the sweeping magnetic field. The LabView program controlled the measurements of the hysteresis loop and in real-time calculated saturation, remanence and the coercive field.

Magnetic domain structure was visualized using the polar Kerr effect. A Carl Zeiss Jenapol optical polarizing microscope with xenon lamp illumination was equipped with a high sensitivity camera with a cooled CCD element and a computer controlled frame grabber. The video signal was electronically processed, subsequently digitized, and then improved by standard image processing techniques (including subtracting the reference image). A computer controlled set-up enabled the adjustment of image acquisition time as well as the generation of pulses of magnetic field oriented perpendicularly to the film plane and characterized by the duration of amplitude and time. The images presented in the paper were acquired in a zero magnetic field. The following procedure was used for magnetic domain generation and visualization: the sample was saturated in magnetic field, then the field was reduced to zero and the reference image I_R recorded. A magnetic field pulse in the opposite direction with the amplitude smaller than saturation was applied and the domain structure image I recorded. The final resulting image was calculated as the difference between the domain structure image I and the reference image I_R.

The MFM technique was used for imaging the magnetic structures beyond the optical resolution [6, 7]. In our case, an NT-MDT NTEGRA system equipped with low magnetic moment MFM tips (MESP-LM, Veeco) was used. A tapping/lift mode enables obtaining of both the topography and the map of magnetic interaction between the sample and a tip.

3. Results and discussion

The influence of the repetition number N on both geometry of the domain structure and magnetization processes is illustrated in Fig. 1, obtained for 0.6 nm thick Co in the [Py (2 nm)/Au (2 nm)]$_{10}$/[Co (0.6 nm)/Au (1.5 nm)]$_N$ series. For small N, large irregular domain structures were observed. The geometry of the domains is determined by defects. Magnetization reversal process, starting from a “black” state by the appearance of limited number of irregular “white” domains, is illustrated in Fig. 1a, b.

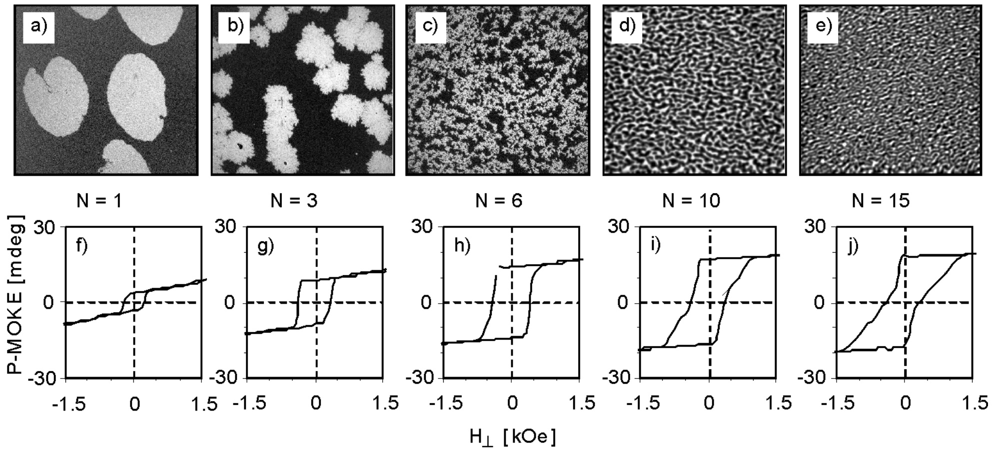

Fig. 1. Domain patterns and corresponding magnetooptic hysteresis loops for [Py (2 nm)/Au (2 nm)]$_{10}$/(Co (0.6 nm)/Au (1.5 nm)]$_N$ samples with various repetition numbers N. Image sizes are: a), b), c) 400×400 μm^2, d), e) 20×20 μm^2. Images a–c) and d), e) were recorded by magnetooptic and MFM techniques, respectively

With the increase of the repetition number N, stronger magnetostatic forces induce the ordering of domains and transition into stripe-like structures with submicrometer sizes is observed. Submicrometer domain structure periods were observed for all samples with large N. The repetition number induced the evolution of magnetization curves as illustrated in Fig. 1f–j. A rectangular hysteresis loop with negative nucleation field H_N in respect to the saturation field H_S was recorded for $N = 1$ (Fig. 1f). Similar loops were discussed in [8]. Upon increasing N, magnetostatic forces stimulate the increase of the saturation field H_S and the increase of the nucleation field H_N which could cross zero and become positive (parallel to H_S).

The influence of cobalt thickness on the magnetic properties of [Py (2 nm)/Au (2 nm)]$_{10}$/[Co (d_{Co})/Au (1.5 nm)]$_{15}$ samples is presented in Fig. 2. A relevant characteristic of such systems ($N = 15$) is the magnetic stripe domain structure. When cobalt thickness increases both the saturation and the nucleation fields increase and the mean size of the domain structures decreases. The effect is connected with the decrease of the domain wall energy in relation to the d_{Co}-induced magnetic anisotropy [5].

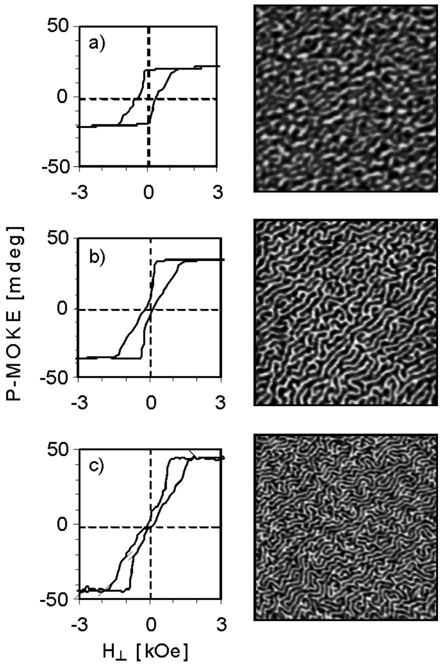

Fig. 2. MOKE hysteresis loops and MFM magnetic domain structure images recorded in samples [Py (2 nm)/Au (2 nm)]$_{10}$/[Co(d_{Co})/Au (1.5 nm)]$_{15}$: a) d_{Co} = 0.6 nm, b) d_{Co} = 1.0 nm, c) d_{Co} = 1.5 nm. Image sizes are 10×10 μm^2

Figure 3 shows magnetic hysteresis loops and domain structure images depending on the non-magnetic Au layer thickness d_{Au} for the fixed magnetic layer thickness d_{Co} = 1.5 nm. The magnetic domain structure period increases versus non-magnetic layer thickness. This is connected with the decrease of magnetostatic forces (a decrease in magnetostatic coupling) connected with d_{Au} increase. Multilayers with d_{Co} = 0.6 nm and d_{Co} = 1.0 nm exhibit a similar evolution with the increase of the gold layer thickness.

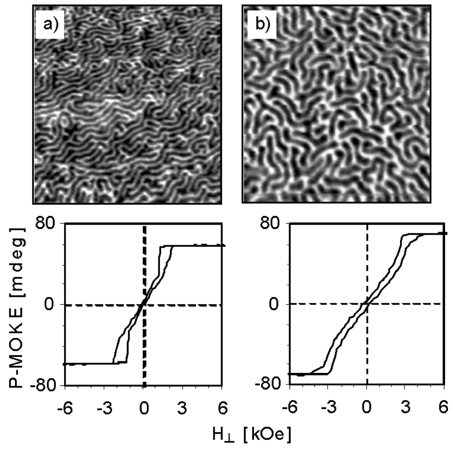

Fig. 3. Domain structure images and MOKE hysteresis loops in samples Au (5 nm)/([Co (1.5 nm)/Au(d_{Au})]$_{15}$ for various Au layer thicknesses: a) d_{Au} = 1.5 nm, b) d_{Au} = 3.0 nm. Image sizes are 5×5 μm^2

One can find a significant influence of the permalloy layer on domain patterns and magnetization processes (Figs. 1, 4). Introduction of Py layers leads to screening of the magnetic field from adjacent Co layers and to the increase of the spacer thickness. Because the magnetostatic coupling between Co layers is weaker, magnetization reversal occurs more independently in a particular layer. This effect is visible in Fig. 4a and b, as domains with multiple shades of gray or in multi-jumps in hysteresis loops. A similar magnetization reversal was observed in [9] for Co/Pt multilayer.

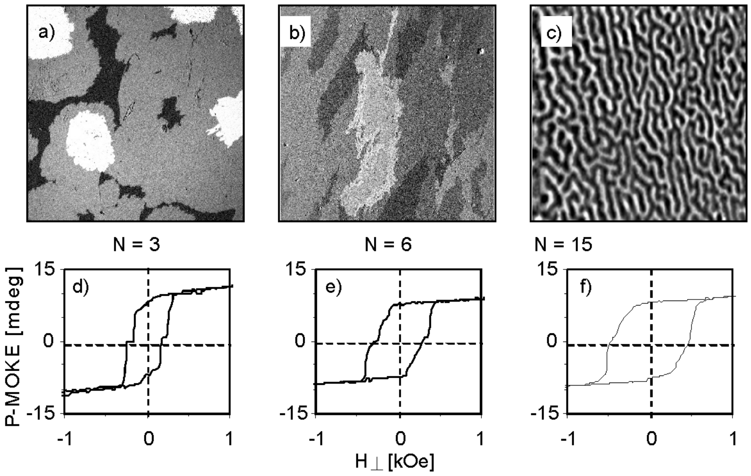

Fig. 4. Domain patterns and corresponding magnetooptic hysteresis loops recorded for [Py (2 nm)/Au (1.5 nm)/Co (0.6 nm)/Au (1.5 nm)]$_N$ for various repetitions numbers: a), d) $N = 3$, b), e) $N = 6$, c), f) $N = 15$. Images sizes are: a), b) 400×400 μm^2, c) 15×15 μm^2

MFM measurements in an external magnetic field applied perpendicular to the sample plane (Fig. 5) demonstrate that the magnetization process goes through domain wall motion. Bubble domain structure was observed while approaching saturation field (Fig. 5c).

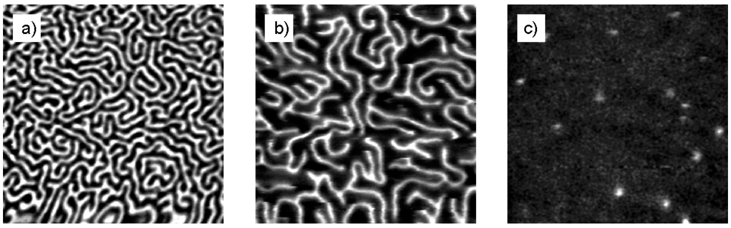

Fig. 5. Evolution of magnetic domain structure in external magnetic field applied perpendicular to the sample plane for Au (5 nm)/[Co (1 nm)/Au (1.5 nm)]$_{15}$: a) $H = 0$ Oe, b) $H = 1.5$ kOe, c) $H = 2.1$ kOe recorded with MFM. Scan size is 5×5 μm^2

4. Conclusion

We have studied the magnetic properties and magnetic domain structures of [Co/Au]$_N$ and [Py/Au/Co/Au]$_N$ multilayers grown with various numbers of repetition

N on different thicknesses of magnetic (Co), non-magnetic (Au) and soft–magnetic (Py) layers. All the analyzed multilayers display a decreased period of magnetic domain structure as the cobalt layer thickness grows, a decreased magnetic domain structure period with the increase number of repetition *N* and an increased domain structure period versus non-magnetic layer thickness.

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