Proceedings of the European Conference "Physics of Magnetism" (PM'08), Poznań 2008

Selective Modification of Magnetic Properties of $Co_1/Au/Co_2/Au$ Multilayers by He Ion Bombardment

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We show that in a $[Co_1/Au/Co_2/Au]_4$ multilayer, where $Co_{1(2)}$ denote Co layers of different thicknesses, a 10 keV He-ion bombardment with a 6×10^{14} ions cm^{-2} dose leads to changes of the easy direction from out-of-plane to in-plane in the thicker Co layers ($t_{Co2} = 1$ nm) while the perpendicular anisotropy of the thinner Co layers ($t_{Co1} = 0.6$ nm) is preserved. The investigated multilayers were obtained by sputtering and the thickness of the Au layers ($t_{Au} = 4$ nm) ensured that a direct coupling between the Co layers (through pinholes) and Ruderman–Kittel–Kasuya–Yosida-like interactions were negligible.

PACS numbers: 61.80.Jh, 75.47.De, 75.70.Cn

1. Introduction

The possibility to locally change properties of magnetic thin film materials is important in view of their applications in the magnetic storage industry. Of particular interest is a non-topographic, i.e., purely magnetic, patterning which can be realized by, e.g., He-ion bombardment (IB) [1, 2]. This technique was successfully applied in systems displaying perpendicular magnetic anisotropy (PMA) to realize a magnetic easy axis (EA) switching in Co/Pt and Co/Au [3] multilayers (MLs). Here we show that the IB with He^+ ions can be used to change the anisotropy direction of the thicker Co layers in a $[Co_1/Au/Co_2/Au]_4$ ML while the perpendicular orientation of magnetization in the thinner Co layers is preserved.

2. Results and discussion

The $[Co_1(0.6\text{ nm})/Au(4\text{ nm})/Co_2(1\text{ nm})/Au(4\text{ nm})]_4$ ML was deposited in an Ar atmosphere using UHV magnetron sputtering. The film was deposited onto a Si(100) substrate with a native oxide covered by a $[Ni_{80}Fe_{20}(2\text{ nm})/Au(3\text{ nm})]_5$ buffer. The sample was bombarded with 10 keV He^+ ions. Vibrating sample magnetometry and magnetoresistance (four-point-probe) measurements (MR) in current-in-plane geometry were performed at room temperature. X-ray diffraction measurements did not give evidence of any significant structural modifications caused by the IB.

Co layers of certain thicknesses sandwiched between Au exhibit PMA [4, 5]. The investigated ML was purposefully designed, with a proper choice of t_{Co}, to obtain the out-of-plane effective anisotropy in the Co_1 and Co_2 layers in an as-deposited state. The inset of Fig. 1b shows the out-of-plane magnetization as a function of the out-of-plane field [$M(H)$] which is characteristic of systems with PMA and a stripe domain structure [6, 7]. We cannot, though, separate contributions to the $M(H)$ dependences coming from the Co_1 and Co_2 layers (from either of the two curves). Two parts of the $M(H)$ dependence can be distinguished when the measuring field is applied in plane (Fig. 1a): changes of a magnetization state taking place in a small field range ($H_{appl} \leq 25$ kA/m) originate predominantly from the NiFe layers of the buffer with EA in-plane while the changes observed in higher fields can be attributed to the Co layers which are magnetized perpendicularly to their EA and which display a typical hard axis behavior. Figure 1 shows the effect of the IB on the magnetic hysteresis of the investigated sample. Noticeably, the part of the hysteresis corresponding to the in-plane anisotropy increased by about 60% as a result of the IB with 6×10^{14} ions cm^{-2} dose (D) (Fig. 1a) (for $D = 3 \times 10^{14}$ ions cm^{-2} the changes were negligible) while the part corresponding to the PMA decreased by 35% (inset of Fig. 1b). In absolute values of the magnetic moment these changes are equal, meaning that in the part of the Co layers the EA changed its orientation to in-plane. This behavior was already observed in the Co/Pt systems [3]. In the Co/Au sys-

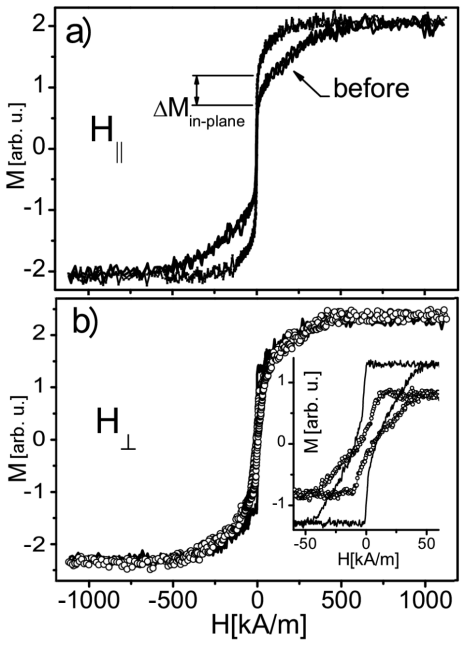

Fig. 1. The field dependences of the magnetic moment of the $[Co_1(0.6\text{ nm})/Au(4\text{ nm})/Co_2(1\text{ nm})/Au(4\text{ nm})]_4$ ML before and after the IB with He^+(10 keV, 6×10^{14} ions cm^{-2}). Part (a) shows the dependences measured with the field applied in the sample plane and (b) for the perpendicular configuration. The inset in (b) shows the small field range hysteresis of the Co layers (thin lines represents the behavior before the IB).

tems, however, the IB leads to the decrease in the PMA which is not necessarily accompanied by the change of the EA direction [3]. The characteristic feature of our MLs is that they contain Co layers of the different thicknesses. It was shown previously that the influence of the IB on the magnetic properties of the Co layers in the NiFe/Au/Co/Au MLs depends strongly on their thickness [8]. Consequently, the effective anisotropies of the Co_1 and Co_2 layers change differently under the influence of the He^+ ions. A standard phenomenological expression describing the effective anisotropy of a single layer reads: $K_{1\text{eff}} = \frac{2K_{1\text{s}}}{t_{\text{Co}}} + K_{1\text{v}} - \frac{1}{2}\mu_0 (M_{\text{S}}^{\text{Co}})^2$. It contains two perpendicular anisotropy constants (the surface $K_{1\text{s}}$ and the volume $K_{1\text{v}}$) and a demagnetization term favoring the in-plane orientation of the magnetization (M_{S}^{Co} is a saturation magnetization of the Co layers). In principle the IB can change both constants as well as the demagnetization term [3]. In the thin Co layers the IB leads to a break-up of the continuous magnetic layer into ferromagnetic, superparamagnetic clusters [3, 8], and/or alloying with Au spacer. The formation of the clusters decreases the in-plane shape anisotropy of the Co layers and in spite of the decreasing PMA ($2K_{1\text{s}}/t_{\text{Co}} + K_{1\text{v}}$) the effective anisotropy favors the perpendicular orientation of the magnetization up to at least $D = 6 \times 10^{14}$ ions cm^{-2}. For the thicker Co layers ($t_{\text{Co}} \geq 0.8$ nm) the IB leads to degradation of Au/Co interfaces, decrease in the PMA, and the switching of the EA direction to in-plane ($K_{1\text{eff}}$ becomes negative). For an intermediate dose, which we used, we expected that the effective anisotropy of the Co_1 layers would favor the perpendicular orientation of the magnetization while in the Co_2 layers it would support the in-plane orientation. Indeed, it is the case in our MLs.

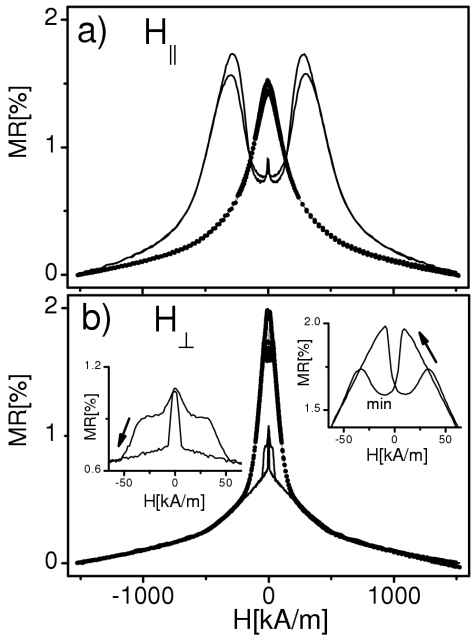

Fig. 2. The field dependences of the resistance of the $[Co_1(0.6\text{ nm})/Au(4\text{ nm})/Co_2(1\text{ nm})/Au(4\text{ nm})]_4$ ML before and after the IB with He^+(10 keV, 6×10^{14} ions cm^{-2}) (Thin lines show the dependences before IB.). Part (a) shows the dependences measured with the field applied in-plane and (b) for the perpendicular configuration. The insets in part (b) show the expanded view of the small field range resistance changes. The arrows show a field sweep direction.

Additional information on the relative orientation of the magnetic moments of the neighboring layers can be obtained from the magnetoresistance measurements. (The Co/Au MLs display a giant magnetoresistance (GMR) [9], i.e., the resistance is proportional to a cosine of the angle between the magnetic moments of the neighboring layers [10].) Figure 2 shows the $R(H)$ dependences of the ML presented in Fig. 1 before and after the IB. The dependence taken before the IB with the field applied in-plane is characteristic of samples with two kinds of the magnetic layers, with different anisotropy fields, being magnetized perpendicularly to the EA direction: the local minimum in the small field range corresponds to the situation when both magnetic moments are parallel [11]. Due to a strong dipolar coupling, the domain structure in each Co layer is replicated, i.e., the domains of the same orientation of the magnetic moment face each other. In the hysteretic range a mean free path of an electron traveling through the structure is comparable with

the domains widths and thus, in the vicinities of the domain walls, a relatively small fraction of the electrons can encounter the domains of the opposite magnetization direction. For the field applied perpendicularly this leads to the GMR-like resistance changes caused by a creation and an annihilation of domains (see the left inset of Fig. 2b) [12]. It is important to note that the character of the $R(H)$ dependences underwent dramatic changes (GMR amplitude changes are irrelevant to our argumentation). Concentrating on the perpendicular configuration, it can be seen that $R(H)$ dependence characteristic of layers with perpendicular anisotropy and the dense domain structure is transformed into the dependence observed for MLs with alternating in-plane and out-of-plane anisotropies in successive layers [12–14].

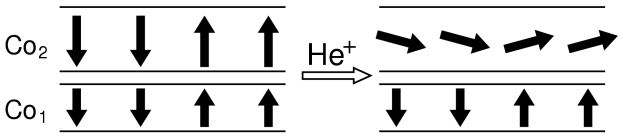

Fig. 3. A cartoon of the multilayer geometry showing the magnetization configuration, at remanence, before and after the IB. The real structure consists of the several magnetic layers.

Summing up, the resistance measurements confirm the observation inferred from the $M(H)$ measurements, namely that the IB led to the switching of the EA direction in the 1 nm thick Co layers (see Fig. 3) while the 0.6 nm thick layers preserved the perpendicular effective anisotropy. Necessary condition for this is that the thickness of the thicker layers is close to a critical value corresponding to a spin reorientation transition from the perpendicular to in-plane orientation.

Acknowledgments

This work was in part supported by the Polish National Scientific Network ARTMAG "Magnetic nanostructures for spintronics".

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