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Magnetic properties of Au/Co/$Ni_{80}Fe_{20}$/Co/Au layered structures

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The influence of an ultrathin cobalt layer at permalloy/gold interfaces in Au/$Ni_{80}Fe_{20}$/Au sandwiches and spin-valve ($Ni_{80}Fe_{20}$/Au/Co/Au)$_N$ multilayers on their magnetic and magnetotransport properties is investigated. We show that an effective magnetic anisotropy of Co/$Ni_{80}Fe_{20}$/Co hybrid structures sandwiched between Au layers can be easily varied by the thickness adjustment of Co and $Ni_{80}Fe_{20}$ layers. We also show that changes of the anisotropy are mainly determined by the Co layer deposited on Au. On the other hand, the influence of Co layer deposited on $Ni_{80}Fe_{20}$ is relatively small. The use of hybrid layers in the spin valve MLs with alternating easy plane and perpendicular anisotropy in consecutive ferromagnetic layers leads to significant changes of their magnetoresistance effect.

1. Introduction

Magnetic thin film layered structures with new magnetic properties are potentially applicable in spintronic devices. This paper presents a study of the magnetic properties of Co/$Ni_{80}Fe_{20}$/Co trilayers sandwiched between gold layers. The main goal was to develop hybrid layers in which the effective anisotropy field H_K^{eff} (the saturation field for the perpendicular configuration) can be varied over a wide range. This can be realized in systems with strong perpendicular surface anisotropy such as Au/Co/Au [1, 2]. In the Au/Co/Au system, H_K^{eff} monotonically increases with increasing Co thickness for $t_{\text{Co}} > t_{\text{crit}}$ (t_{crit} – critical cobalt thickness corresponding to the spin reorientation transition) due to the competition between the shape and surface anisotropy.

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It is to be expected that replacing a single Co layer in the Au/Co/Au system with $Co/Ni_{80}Fe_{20}/Co$ trilayer could significantly influence H_K^{eff}. The Co thickness range corresponding to the creation of continuous Co layer in which the surface anisotropy contribution increases gradually, seems to be especially interesting.

The giant magnetoresistance effect and magnetization reversal in spin valve (SV) type $(F_{\parallel}/S/F_{\perp}S)_N$ ($F_{\parallel}$, $F_{\perp}$ – ferromagnetic layers with in-plane and out-of-plane anisotropy, respectively, S – spacer, N – repetition number) multilayers with the $[Au/Ni_{80}Fe_{20}/Au/Co_{\perp}/Au]$ structure where permalloy layer was replaced with the $Co/Ni_{80}Fe_{20}/Co$ trilayer was discussed in detail in our previous paper [3]. The paper presented correlations between resistance and magnetization dependences and explained how to determine H_K^{eff} of $Co/Ni_{80}Fe_{20}/Co$ layer ($F_{\parallel}$). We explained there how the changes of the H_K^{eff} of $F_{\parallel}$ layer influence effects associated with the presence of a domain structure. The present paper describes supplementary investigations of structures with different $F_{\parallel}$. The main purpose was to determine the differences between H_K^{eff} (t_{Co}) dependences of the structures having a Co layer at both interfaces ($Co/Ni_{80}Fe_{20}/Co$) or at only one interface ($Co/Ni_{80}Fe_{20}$ or $Ni_{80}Fe_{20}/Co$). It should be noted that investigated bi- and trilayers, because of their total thickness much lower than the domain wall thickness, can be treated as magnetically homogeneous [4], i.e. with magnetization vector constant along the normal to the film surface.

2. Experimental

The multilayers were prepared by magnetron sputtering. Preparation details are given in the previous paper [5]. The value of H_K^{eff} as a function of thickness of $Ni_{80}Fe_{20}$ and Co layers was determined from $M(H)$ dependences measured using magnetooptical Kerr effect in polar configuration (MOKE, 1mm spot size). MOKE measurements were performed on the sandwich structure: substrate/buffer/Co-wedge/$Ni_{80}Fe_{20}$-steps/Co-wedge/Au. Si(100) substrate (15×20 mm^2 in size) was covered with a buffer $(Ni_{80}Fe_{20}\text{-}2nm/Au\text{-}3\ nm)_{10}$ multilayer. The multilayered buffer ensured the topmost Au layer with large crystal grain size (20 nm lateral dimensions determined by STM) and (111) texture. The Co thickness in the wedges was varied from 0 to 1 nm and the thickness gradient was parallel to the long edge of the sample. The permalloy layer was introduced in a form of three steps (5 mm wide, running perpendicularly to the Co wedge gradient) with thickness t_{NiFe} = 0, 0.25, 0.5 nm. Three series of the SV structures were also deposited. In SV samples with the $(F_{\parallel}/S/F_{\perp}/S)_N$ structure, 2.2 nm thick Au spacer ensured a negligibly weak interaction between $F_{\parallel}$ and $F_{\perp}$ [5]. 0.8 nm thick Co layer was used as $F_{\perp}$, later denoted as $Co_{\perp}$ (for $0.3 \le t_{Co} \le 1.2$ nm perpendicular anisotropy is observed in this type of multilayers). The ferromagnetic $F_{\parallel}$ layers with in-plane anisotropy were prepared as tri- or bilayers: $Co/Ni_{80}Fe_{20}/Co$ (series (SV-a)), $Co/Ni_{80}Fe_{20}$ (series (SV-b)) and $Ni_{80}Fe_{20}/Co$ (series

(SV-c)). The total thickness of the $F_{||}$ layers was kept constant at 3.2 nm and t_{Co} thickness was varied. The t_{Co} values were 0, 0.2, 0.4, 0.6 for all series and additionally t_{Co} = 1.6 nm for series (SV-a) (in this case $F_{||}$ was a single 3.2 nm thick Co layer). H_K^{eff} value of SV multilayers with a number of repetitions N = 10 was determined from hysteresis loops ($M(H)$ dependences) measured with a vibrating sample magnetometer (VSM) and from magnetoresistance measurements ($R(H)$ dependences). All measurements were carried out at room temperature with magnetic field perpendicular to the sample surface.

3. Results and discussion

Figure 1a shows a typical $M(H)$ dependence measured using MOKE for sandwich samples. Its shape indicates clearly that it is a superposition of two hysteresis loops. One loop comes from the reversal of $Ni_{80}Fe_{20}$ (buffer) layer which saturates at about 0.6 T. This corresponds to the shape anisotropy of that layer ($4\pi M_S^{NiFe}$). The other one originates from the reversal of the investigated (Co/NiFe/Co) trilayer, with much smaller H_K^{eff} value. The contribution from the trilayer is clearly visible due to a significant difference between effective anisotropy field of the buffer and the trilayer, and a weak coupling between the two across the Au spacer [5]. It allowed us to determine H_K^{eff} of Co/$Ni_{80}Fe_{20}$/Co trilayer and Co film sandwiched between Au layers.

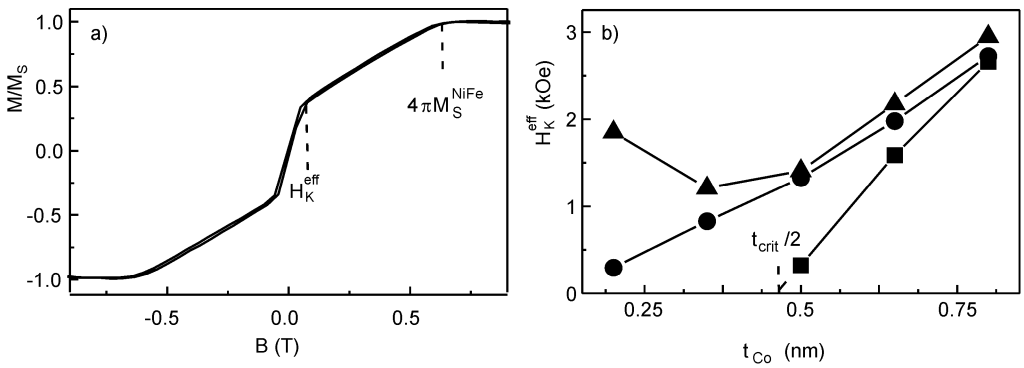

Fig. 1. Exemplary hysteresis loop (a) and the dependence of effective anisotropy field H_K^{eff} on cobalt layer thickness t_{Co} in [($Ni_{80}Fe_{20}$/Au)$_{10}$/Co/$Ni_{80}Fe_{20}$-t_{NiFe}/Co/Au] layered films for t_{NiFe} = 0 nm (■); 0.25 nm (●); 0.5 nm (▲) (b)

Figure 1b shows the effective anisotropy field H_K^{eff} of the trilayer as a function of Co thickness ($0.2 \le t_{Co} \le 0.8$ nm) for three various permalloy sublayer thicknesses t_{NiFe} = 0, 0.25 and 0.5 nm (for t_{NiFe} = 0, the total thickness of Co layer is $2t_{Co}$). The H_K^{eff} (t_{Co}) dependence of a single Co layer is typical of a system with a significant contribution of surface anisotropy. The critical Co thickness (determined from

H_K^{eff} (t_{Co}) dependence for $t_{\mathrm{NiFe}} = 0$, Fig. 1b) corresponding to magnetization reorientation from out-of-plane to in-plane is about 0.9 nm. $H_K^{\mathrm{eff}}(t_{\mathrm{Co}})$ monotonically increases for $t_{\mathrm{Co}} > t_{\mathrm{crit}}$ indicating a diminishing contribution of surface anisotropy to the effective anisotropy described by the well-known equation $K_{\mathrm{eff}} = K_{\mathrm{V}} + 2K_{\mathrm{S}}/t$, ($K_{\mathrm{V}}$ and K_{S} – volume and surface anisotropy constants, respectively). For permalloy thickness $t_{\mathrm{NiFe}} = 0.5$ nm, the function $H_K^{\mathrm{eff}}(t_{\mathrm{Co}})$ exhibits a minimum at $t_{\mathrm{Co}} \approx 0.4$ nm. The observed dependence probably reflects a weak contribution of the Au/Ni-Fe interface to K_{S} and the fact that the contribution of Au/Co interface to K_{eff} is the largest when Co layer becomes continuous. It should be noted that Co layer grown on Au(111) becomes continuous for the thickness greater than two atomic layers [6].

For small t_{Co}, the trilayer with an intermediate permalloy thickness $t_{\mathrm{NiFe}} = 0.25$ nm exhibits a linear increase of H_K^{eff} (t_{Co}) with the slope considerably smaller comparing to the sample without permalloy. The comparison of the H_K^{eff} (t_{Co}) dependences for Au/Co/Au and Au/Co/$Ni_{80}Fe_{20}$/Co/Au structures indicates that the introduction of an ultrathin NiFe layer in the middle of the Co layer results in a strong decrease of t_{crit}.

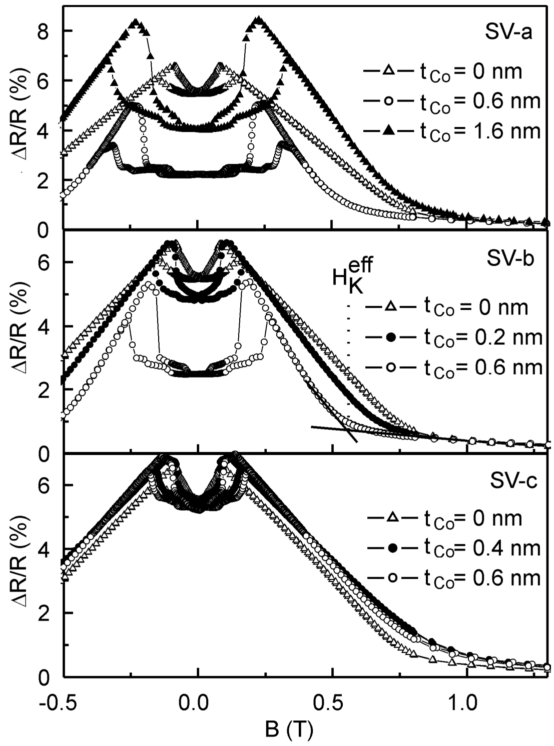

Fig. 2. Magnetoresistance effect of three sets of $(F_{\|}/S/F_{\perp}/S)_{10}$ spin valve multilayers (see also description in Experimental) with S = Au 2 nm, $F_{\perp} = Co_{\perp}$ 0.8 nm and $F_{\|}$ = Co/NiFe/Co (SV-a), $F_{\|}$ = Co/NiFe (SV-b), $F_{\|}$ = NiFe/Co (SV-c) with $t_{F\|} = 3.2$ nm, the thicknesses of Co layers are given in the figure; $\Delta R/R$ dependences are shown in a limited field range for clarity

Figure 2 shows $\Delta R/R(H)$ dependences as a function of Co thickness for all three types of SV structures. It can be seen that placing an ultrathin Co layer at both interfaces or at the bottom interface only leads to similar changes in magnetoresistance dependences. The changes in magnetoresistance indicate the decrease of H_K^{eff} value for $t_{\text{Co}} \leq 0.6$ nm (Figs. 2a, b). Simultaneously, the effects associated with the presence of the domain structure, i.e. a sudden resistance decrease in small fields, are stronger. On the contrary, in structures with a Co layer at the upper interface only, the changes of $R(H)$ dependence indicate slight increase of H_K^{eff} with t_{Co} and small changes in magnetic fields corresponding to the presence of the domain structure.

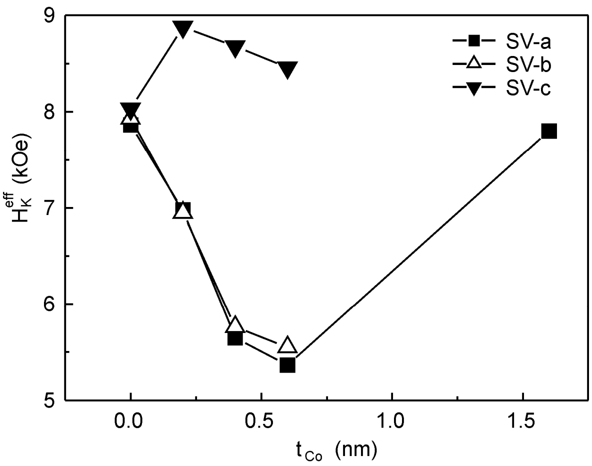

Fig. 3. Effective anisotropy field H_K^{eff} as a function of cobalt layer thickness determined from $\Delta R/R(H)$ dependences measured for three series of spin valve multilayers

Figure 3 shows the effective anisotropy field for all three series of spin valves as a function of cobalt thickness. A comparison of the dependences shown in Fig. 1 for $t_{\text{NiFe}} = 0.5$ nm and those shown in Fig. 3 reveal that $H_K^{\text{eff}}(t_{\text{Co}})$ dependences for structures with Co layer at both interfaces and at the bottom interface only are similar. For both cases described above, $H_K^{\text{eff}}(t_{\text{Co}})$ shows a local minimum which, in our opinion, is due to the growth of a continuous Co layer on gold. The differences in H_K^{eff} values for the Co/Ni$_{80}$Fe$_{20}$/Co structures shown in Figs. 1 and 3 originate from different permalloy layer thicknesses. The presence of a weak maximum in $H_K^{\text{eff}}(t_{\text{Co}})$ dependence for structures with Co layer at the upper interface only indicates that the effective perpendicular anisotropy of Co layers is lower (compare the discussion of Fig. 1). The initial increase of H_K^{eff} with t_{Co} is thus the result of the increase of the effective magnetization of NiFe/Co bilayer. At higher Co coverage, the perpendicular anisotropy leads to a slow decrease of H_K^{eff}.

4. Conclusions

Hybrid thin film samples consisting of Co and $Ni_{80}Fe_{20}$ layers sandwiched between Au were investigated. It was shown that the insertion of thin cobalt layer at the lower interface of the $Au/Ni_{80}Fe_{20}/Au$ structure, resulting in $Au/Co/Ni_{80}Fe_{20}/Au$ structure, significantly decreases the easy-plane type anisotropy field. The anisotropy field of hybrid layers can be controlled in a wide range by permalloy and cobalt layers thickness. It was also shown that this property of hybrid layers can be applied to a significant modification of magnetoresistance dependences of spin valves with alternating easy plane and perpendicular magnetic anisotropy in consecutive ferromagnetic layers.

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