Materials Science-Poland, Vol. 25, No. 4, 2007

Magnetic and magnetoresistive properties of CoFe/Au/Co/Au multilayered structures[*]

B. SZYMAŃSKI[**], M. URBANIAK, F. STOBIECKI

Institute of Molecular Physics, Polish Academy of Sciences,
ul. Smoluchowskiego 17, 60-179 Poznań, Poland

Sputter deposited ($Co_{90}Fe_{10}$ t_{CoFe}/Au 2.7nm/Co 0.6nm/Au 2.7nm$)_{10}$ multilayers with t_{CoFe} in the 0.4–3.0 nm range were investigated. Magnetic reversal *M*(*H*) and magnetoresitance *R*(*H*) curves were measured. For $t_{CoFe} \geq 1.2$ nm, the *R*(*H*) characteristics are similar to that of the prototype system (NiFe/Au/Co/Au), i.e. the system characterized by alternating in plane (NiFe) and out-of-plane (Co) magnetic anisotropy. However, for smaller t_{CoFe}, the effective anisotropy of CoFe layers switches from the in-plane anisotropy to the perpendicular one. This transition is a reason of a strong decrease of the GMR amplitude for $t_{CoFe} < 1.2$ nm. The relatively large values of GMR amplitude (≈ 7%) and saturation field (900 kA/m) were obtained for sample with $t_{CoFe} = 3$ nm, measured in perpendicular field configuration. The result indicates a distinct improvement of parameters important for application of studied films as magnetoresistive sensors characterized by the linear *R*(*H*) dependence in a broad range of magnetic field.

Key words: *magnetic multilayers; perpendicular magnetic anisotropy; GMR sensor*

1. Introduction

In our previous papers [1–3], we have demonstrated that $(NiFe/Au/Co/Au)_N$ multilayers (MLs) characterized by in-plane and out-of-plane anisotropy for Ni–Fe and Co layers, respectively, can by applied as magnetoresistive sensors for quantitative measurements of magnetic field up to 500 kA/m. To extend further the range of magnetic field corresponding to the linear *R*(*H*) dependence we have replaced $Ni_{80}Fe_{20}$ layers by $Co_{90}Fe_{10}$, i.e., by layers with a higher saturation magnetization. The thickness of Au layer t_{Au}=2.7 nm was chosen to ensure a negligible coupling between ferromagnetic layers. Because properties of the Co layer sandwiched between gold layers are well known [1] it allows us to determine magnetic properties of the $Co_{90}Fe_{10}$ layer, the function of t_{CoFe} from the analysis of *M*(*H*) and *R*(*H*) curves. We have chosen the layer with $t_{Co} = 0.6$ nm because it is continuous and shows a strong perpendicular anisotropy.

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[*] Presented at the Conference of the Scientific Network "New Materials for Magnetoelectronics – MAG-EL-MAT 2007", Będlewo near Poznań, 7–10 May 2007.

[**] Corresponding author, e-mail: szyman@ifmpan.poznan.pl

2. Experimental

A set of ($Co_{90}Fe_{10}$ t_{CoFe}/Au 2.7 nm/Co 0.6 nm/Au 2.7 nm$)_{10}$ MLs with t_{CoFe} in the range from 0.4 to 3.0 nm was prepared using UHV magnetron sputtering [1]. The samples were deposited at room temperature onto naturally oxidized Si(100) wafers. A good periodic structure of MLs was confirmed by low- and high-angle X-ray diffraction. Magnetoresistance $R(H)$ and magnetization reversal $M(H)$ were studied at room temperature for a magnetic field applied perpendicular to the sample plane. $M(H)$ loops were recorded with vibrating sample magnetometer. $R(H)$ curves were recorded with current in plane configuration (CIP). The GMR(H) dependence was determined as $[R(H) - R(1600\ \text{kA/m})]/R(1600\ \text{kA/m})$ where R(1600 kA/m) is electrical resistance at H = 1600 kA/m. The maximum value of GMR(H) defines the GMR amplitude.

3. Results and discussion

The exemplary $M(H)$ and $R(H)$ curves of ($Co_{90}Fe_{10}$ t_{CoFe}/Au 2.7 nm/Co 0.6 nm/Au 2.7 nm$)_{10}$ MLs ($0.4 \le t_{CoFe} \le 3.0$ nm) are shown in Fig. 1. For $t_{CoFe} \ge 1.2$ nm (Figs. 1a–c), the magnetization reversals of CoFe and Co layers are distinct and we can determine fields corresponding to the nucleation (H_N^{Co}) and annihilation (H_A^{Co}) of stripe domains

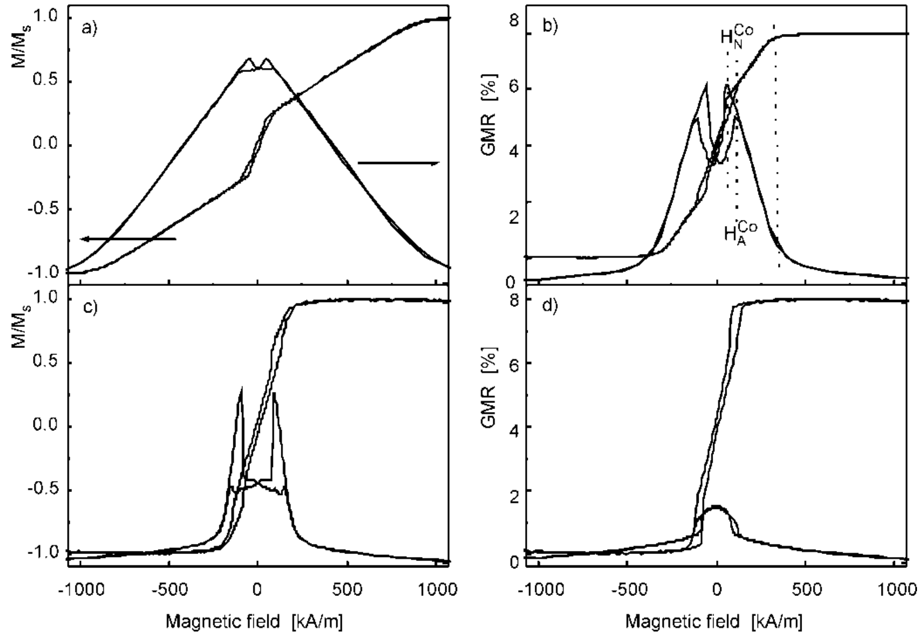

Fig. 1. Exemplary hysteresis loops and magnetoresistance curves of ($Co_{90}Fe_{10}$ t_{CoFe}/Au 2.7 nm/Co 0.6 nm/Au 2.7 nm$)_{10}$ MLs with various t_{CoFe}: a) 3.0 nm, b) 1.5 nm, c) 1.2 nm, d) 1 nm

in Co layers as well as saturation field of CoFe layers (H_S^{CoFe}). This behaviour is similar to that observed for ($Ni_{80}Fe_{20}$/Au/CoAu) multilayers [3] and therefore $M(H)$ and $R(H)$ dependences can be described in a similar way. Due to thick spacer layer ($t_{Au} = 2.7$ nm), the interlayer coupling between ferromagnetic layers is weak (except dipolar coupling caused by the domain structure) and their magnetization reversals can be treated as nearly independent of each other. However, as we have mentioned in [3], this is true for H_N^{Co}, $H_A^{Co} \leq |H| \leq H_S^{CoFe}$ (non-hysteretic range) where the coherent rotation of magnetization in CoFe layers takes place and the magnetization of Co layers is aligned along the field direction. In this field range, $R(H)$ dependences are linear and reversible. On the contrary, for $|H| \leq H_N^{Co}$, H_A^{Co} a strong ferromagnetic coupling originating from the stripe domain structure of Co layers strongly influences the magnetic configuration of the system. As a consequence, the resistance is reduced. In particular, at $H = 0$ the angle Θ between the magnetization directions of CoFe and Co is lower than 90° (for MLs with zero coupling, the mutually perpendicular orientation of magnetization in Co and CoFe layers is expected at remanence).

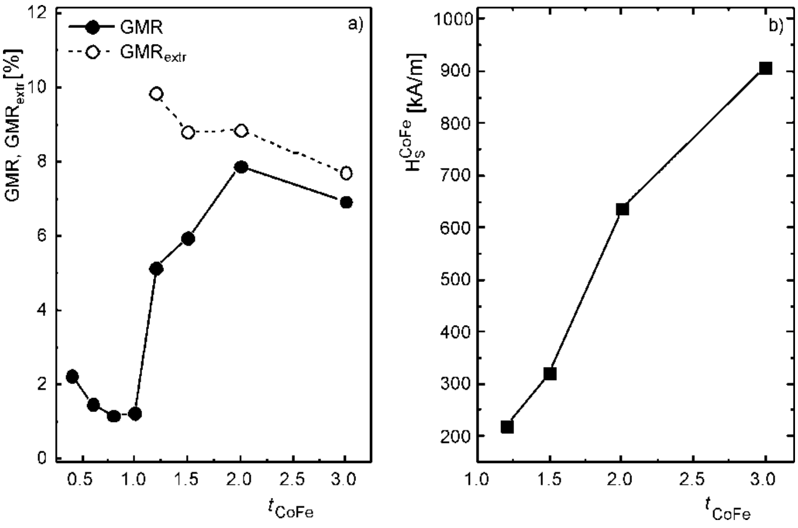

Fig. 2. The GMR amplitude and the extrapolated GMR_{extr} values (a) as well as the saturation field H_S^{CoFe} of the MLs as a function of t_{CoFe} (b). The extrapolated GMR values were determined by extrapolation of the linear part of GMR curves to zero field

The main difference between previously investigated ($Ni_{80}Fe_{20}$/Au/Co/Au) and ($Co_{90}Fe_{10}$/Au/Co/Au) multilayers concerns changes of the saturation field and the GMR amplitude with the thickness of NiFe and CoFe, respectively. For (NiFe/Au/Co/Au) MLs both dependences, i.e., GMR(t_{NiFe}) and $H_S(t_{NiFe})$ are presented in Fig. 3 in [2], for (CoFe/Au/Co/Au) MLs they are shown in Fig. 2. In GMR(t_{CoFe}) dependence an abrupt increase of GMR value is observed at $1 \leq t_{CoFe} \leq 1.2$ nm (compare also Figs. 1c and d). This effect is related to the transition of effective magnetic anisotropy of CoFe layers from the perpendicular (for $t_{\mathrm{CoFe}} \leq 1$ nm) to in-plane (for $t_{\mathrm{CoFe}} \geq 1.2$ nm). The anisotropy changes with the thickness of CoFe layers are caused by the competition between volume and surface anisotropy [4]. Due to high concentration of Co in CoFe layers, the thickness at which the reorientation of magnetization takes place is reduced only by 0.2 nm as compared to Co layers, sandwiched between Au. The field range at which the linearity requirement of $R(H)$ is fulfilled, is crucial for application of investigated films as magnetoresistive sensors. This range is determined mainly by the saturation field of CoFe layers ($H_{\mathrm{S}}^{\mathrm{CoFe}}$) which is the measure of the anisotropy. The $H_{\mathrm{S}}^{\mathrm{CoFe}}$ (t_{CoFe}) dependence for $t_{\mathrm{CoFe}} \geq 1.2$ nm is demonstrated in Fig. 2b and indicates that for (CoFe/Au/Co/Au) MLs, $H_{\mathrm{S}}^{\mathrm{CoFe}}$ can be tuned in a broad range. In particular, for the MLs with $2 \leq t_{\mathrm{CoFe}} \leq 3$ nm the larger range of linear $R(H)$ dependence and the larger GMR amplitude as for (NiFe/Au/Co/Au) MLs can be simultaneously realized.

Finally, we will discuss specific changes of the magnetoresistance effect of our (CoFe/Au/Co/Au) MLs with the thickness of CoFe layers in the range corresponding to the magnetic reorientation transition. The (CoFe 1.2 nm/Au 2.7 nm/Co 0.6 nm/Au 2.7 nm)$_{10}$ sample is characterized by in-plane and perpendicular anisotropy of CoFe and Co layers, respectively. Due to a very weak anisotropy (low value of saturation field), the reaction of the 1.2 nm thick CoFe layer on stray fields caused by domains of Co layers is very strong (Fig. 1c). Therefore, for this sample the resistance is strongly reduced at $H = H_N$ and the difference between the measured GMR amplitude and the extrapolated GMR value (corresponding to $\Theta = \pi/2$) is particularly large (Fig. 2a). Moreover, the range of reversible changes in $R(H)$ is also strongly reduced as compared to MLs with larger t_{CoFe}. For (CoFe/Au/Co/Au) MLs with $t_{\mathrm{CoFe}} \leq 1$ nm (Fig. 1d), the effective anisotropy of CoFe layers is perpendicular. Thus, the MLs are composed of two types of ferromagnetic layers each having perpendicular anisotropy. Their $R(H)$ dependences are distinctly different from those analyzed previously. The $R(H)$ and $M(H)$ dependences for ML with $t_{\mathrm{CoFe}} = 1$ nm are presented in Fig. 1d. The character of $R(H)$ dependence for other MLs with $t_{\mathrm{CoFe}} < 1$ nm is similar. For these samples, the linear and reversible range of the $R(H)$, characteristic of MLs with alternating in-plane and perpendicular anisotropy (Fig. 1a–c), is not present (small changes of resistance for $|H| \geq H_{\mathrm{N}}$ (H_{A}) are related to the electron scattering on superparamagnetic precipitations [5]). The resistance increase at H_{N} and decrease at H_{A} (Fig. 1d) can be explained as follows. At $H = H_{\mathrm{N}}$, the stripe domain structure is formed simultaneously in Co and CoFe layers. Due to a strong dipolar coupling ferromagnetic in nature, the shapes and dimensions of the domains and orientations of their magnetic moments are the same in all ferromagnetic layers. However, for such a magnetic configuration, a part of electrons traversing the structure in the vicinity of the domain walls interacts with ferromagnetic domains characterized by antiparallel configuration of magnetizations. The probability of this process, as compared to scattering in ferromagnetic regions with the parallel magnetic moment configuration, is negligible in MLs with large domains.

However, this effect can be essential in MLs with narrow stripe or labyrinth domains. For investigated layered films with perpendicular anisotropy of all ferromagnetic layers and stripe domain structure, the GMR effect measured in CIP geometry is about 1% (Fig. 2a). This value is about twenty times smaller than that expected for transition from antiparallel to parallel magnetic configuration. The latter should be twice larger than the extrapolated GMR amplitude corresponding to the transition between mutually parallel and perpendicular magnetic configurations (Fig. 2a).

4. Conclusions

Magnetic and magnetoresisitve properties of sputtered ($Co_{90}Fe_{10}$ t_{CoFe}/Au 2.7 nm/Co 0.6 nm/Au 2.7 nm$)_{10}$ MLs with t_{CoFe} in the range from 0.4 nm to 3.0 nm were investigated. We have found that for the $2 \le t_{\mathrm{CoFe}} \le 3$ nm the $R(H)$ dependences are linear and non-hysteretic and show GMR amplitudes of 6–8%. Thus, the replacement of NiFe layer by CoFe layer results in a considerable improvement of parameters important for the application of investigated MLs as magnetic field sensors for quantitative measurements of magnetic field in a broad range. We have also demonstrated that $R(H)$ measurements are a very sensitive tool for determination of magnetic reorientation transition in ultrathin ferromagnetic films.

Acknowledgements

Supported by the State Committee for Scientific Research with Grant No. 3 T08A 03127 and from the science resources as a joint research program within the scientific network "New materials and sensors for optoelectronics, informatics, energetic and medicine".

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Received 4 May 2007
Revised 2 July 2007