Proceedings of the European Conference Physics of Magnetism 2011 (PM'11), Poznań, June 27–July 1, 2011

Giant Magnetoresistance of $[Ni_{80}Fe_{20}/Au/Co/Au]_N$ Multilayers Deposited on Flexible Substrates

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Magnetic hysteresis and magnetoresistance of $[Ni_{80}Fe_{20}/Au/Co/Au]_{10}$ multilayers displaying giant magnetoresistance and sputtered on a flexible polypropylene substrates (an adhesive tape) is investigated. The magnetoresistive properties are very similar to those found in films prepared under the same conditions on Si(100) substrates. It is demonstrated, too, that a bendability of the substrates can be utilized to form cylindrically shaped magnetoresistive sensors with reduced anisotropy of the effect.

PACS: 75.47.De, 75.70.Cn

1. Introduction

Since its discovery in 1988 the giant magnetoresistance effect (GMR) has found numerous applications in electronics [1]. It has been used in read-heads, in random access memories [2], in magnetic field sensors, and in bio-science [3]. Parallel to the rapid development of spintronics [4] there was a great progress in the so-called flexible electronics [5–7] which aims at obtaining flexible displays, electronic circuits, solar cells [8] etc. In the meantime it was shown by Parkin [9] that systems displaying GMR can be easily sputter-deposited on organic layers placed by spin-coating on Si substrates or even on free-standing organic films (mylar, kapton, ultem). In successive works it was shown that an electrochemical synthesis, too, can be used for the deposition of the flexible GMR sensors [10]. Recently it was demonstrated that flexible magnetoelectronics can provide the mechanically tunable GMR sensors exhibiting very high magnetoresistance ratio and high mechanical stability [11].

In this contribution we show that the principles of flexible electronics can be used to improve performance of inherently anisotropic GMR of multilayers (MLs). We present the results concerning the $[Ni_{80}Fe_{20}/Au/Co/Au]_N$ MLs which we have previously shown to possess interesting magnetoresistive properties related to a relative orientation of magnetic easy axes in the neighboring magnetic sublayers [12, 13]. It was demonstrated there that a perpendicular magnetic anisotropy (PMA) of the Co sublayers results in an almost linear magnetoresistance as the magnetic moments of the $Ni_{80}Fe_{20}$ layers reverse in perpendicularly applied magnetic field.

2. Experimental

The $[Ni_{80}Fe_{20}(2\text{ nm})/Au(2\text{ nm})/Co(t_{Co})/Au(2\text{ nm})]_{10}$ spin-valve-like MLs investigated in this study have been deposited at room temperature (RT) by magnetron sputtering on the naturally oxidized Si(100) substrates and on a 25 μm thick Scotch® Tape 508 pressed to the Si(100) substrate (it is a common office-use adhesive tape composed of bi-oriented polypropylene). The sputtering gas was argon (at 10 Pa) and sputtering rates were 0.06, 0.05, and 0.045 nm/s, for Au, $Ni_{80}Fe_{20}$, and Co, respectively. The unwound tape was not cleaned before the deposition of MLs (compare Ref. [9]). The MLs deposited on the tape used the same piece of the Si substrate as the one deposited directly on Si and were produced in one sputtering process. The magnetoresistance (MR) was measured at RT with a four-point or a pseudo four-point method (see left inset of Fig. 3) and calculated relative to the resistance at 1410 kA/m. Magnetization hysteresis curves, $M(H)$, were measured with a vibrating sample magnetometer at RT. The attempts at X-ray diffractions experiments on the MLs deposited on the polypropylene were inconclusive. Probably the tape did not perfectly adhere to the Si substrate giving some waviness and that lead to a significant broadening of diffraction peaks making the analysis unreliable.

3. Results and discussion

The exemplary MR(H) dependences obtained for $[Ni_{80}Fe_{20}/Au/Co/Au]_{10}$ ML are shown in Fig. 1. It can be seen that the curves measured for the MLs deposited on different substrates do not differ significantly. The amplitudes of GMR are approximately equal but there is a small difference in the values of the saturation fields depending on the substrate. The difference is more pronounced for in-plane field (Fig. 1a), which corresponds to the reversal of the Co sublayers with perpendicular anisotropy. It points to the influence of the substrate on the perpendicular anisotropy of those sublayers. It should be emphasized that as the PMA of the Co sublayers originates from the surface anisotropy of the Co/Au interfaces [13, 14] it is sensitive to any changes of its structure caused by an increased roughness of the plastic substrates [11]. In perpendicular configuration the MR(H) dependences (outside the hysteretic range) are almost indiscernible. The discrepancy between H_S^{Co} values in parallel configuration is negligible (603 kA/m and

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611 kA/m for MLs deposited on Si(100) and polypropylene substrate, respectively). In the hysteretic range (see the inset of Fig. 1) the dependences differ slightly, but the characteristic fields of the Co sublayers reversal (nucleation and annihilation fields of the domain structure — see Fig. 1 of Ref. [12]) are the same. We have shown earlier [13] that there is a clear correlation between $R(H)$ and $M(H)$ dependences in [$Ni_{80}Fe_{20}$/Au/Co/Au]$_N$ MLs.

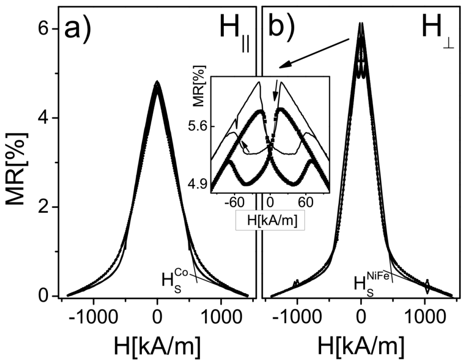

Fig. 1. Magnetoresistance dependences measured on [$Ni_{80}Fe_{20}$(2 nm)/Au(2 nm)/Co(0.6 nm)/Au(2 nm)]$_{10}$ MLs sputtered directly on the Si(100) substrates (lines) and on the adhesive tape (dots). Part (a) shows the measurements performed with magnetic field applied in-plane, part (b) with perpendicular field. The inset shows the low field range of magnetoresistance dependence in the perpendicular configuration.

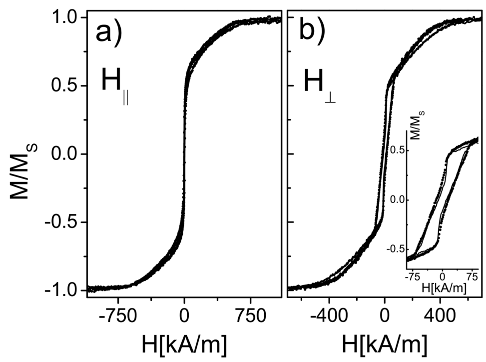

Fig. 2. $M(H)$ dependences measured on [$Ni_{80}Fe_{20}$(2 nm)/Au(2 nm)/Co(0.6 nm)/Au(2 nm)]$_{10}$ MLs sputtered directly on the Si(100) substrates (lines) and on the adhesive tape (dots). Part (a) shows the measurements performed with magnetic field applied in-plane, part (b) with perpendicular field. The inset of part (b) shows the low field range of the latter measurement.

Magnetic properties of [$Ni_{80}Fe_{20}$/Au/Co/Au]$_{10}$ MLs are only little affected by the kind of substrate, too (Fig. 2). The hysteresis curves in both parts are almost indistinguishable. An inset of Fig. 2b proves that the nucleation field of the domain structure in Co sublayers as well as annihilation field differ insignificantly (compare the inset of Fig. 1). A surface density of magnetic moment (relative to the surface of the sample) calculated for a similar ML is higher in the sample deposited directly on Si by only about 2%, which is within an experimental error of our experiment.

Recapitulating, it may be said that the magnetic and magnetoresistive properties of [$Ni_{80}Fe_{20}$/Au/Co/Au]$_{10}$ MLs deposited on the Si substrates and on polypropylene are very similar. One of the reasons may be the relative insensitivity, in comparison to the Ruderman–Kittel–Kasuya–Yosida (RKKY)-coupled MLs [15], of spin-valve-like systems to the small structural changes.

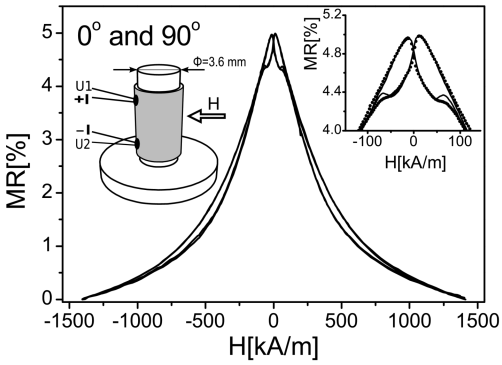

Fig. 3. Magnetoresistance dependences measured on [$Ni_{80}Fe_{20}$(2 nm)/Au(2 nm)/Co(0.6 nm)/Au(2 nm)]$_{10}$ ML sputtered on the adhesive tape which was afterwards wound around the cylinder (see left inset). Two measurements are shown (line and dots). In both cases field is applied perpendicularly to the axis of the cylinder, but the direction is changed by 90°. Left inset: The schematic view of the sample holder used for the measurement of magnetoresistance of wound ML. It is made out of plexiglas. The measured ML (gray area) is wound (without the overlap) around the cylinder of 3.6 mm diameter. The electrode wires are attached with a silver paint in the pseudo four-point configuration. The external magnetic field was applied perpendicularly to the axis of the plexiglas cylinder.

In the following we show that the elastic properties of the polypropylene tape can be used for easy constructing a quasi-isotropic magnetic field sensor. To that end, we have prepared a special sample holder (left inset of Fig. 3) to which we have attached a 10×12 mm^2 stripe of ML deposited on the polypropylene adhesive tape. The stripe was previously mechanically detached from the Si substrate. The adhesive properties of the tape did not noticeably deteriorate during the sputtering and the subsequent handling so that ML was stuck to the cylinder of the holder by a slight pressing.

The magnetoresistance of the sample wound around the cylinder is shown in Fig. 3. As expected, we observe that the magnetoresistance dependence is almost isotropic. There are small differences visible in a small field range (inset of Fig. 3) which we cannot explain. They can be due to imperfect alignment of the tape and/or due to some defects introduced during unmounting and mounting of the sample. The very small radius of the cylinder confirms the high bendability of the GMR system deposited on the polypropylene which is necessary for any practical flexible electronics applications [11, 16]. The mechanical stability of our MLs seems to be worse than that of Chen's samples [11] since after 100 manual bending/unbending cycles the GMR amplitude of $[Ni_{80}Fe_{20}(2\,nm)/Au(2\,nm)/Co(0.8\,nm)/Au(2\,nm)]_{10}$ ML measured in in-plane configuration decreased by 25%. It should be noted, though, that to make the bending experiment we had to detach our sample (ML+adhesive tape) from the Si substrate introducing some undefined stresses in the ML and the bending radius was only about 2.5 mm. This could lead to an increased cracking [8] and deterioration of the GMR effect.

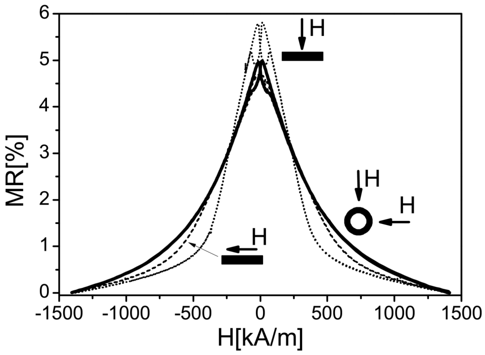

Fig. 4. Magnetoresistance dependence measured on $[Ni_{80}Fe_{20}(2\ nm)/Au(2\ nm)/Co(0.6\ nm)/Au(2\ nm)]_{10}$ ML sputtered on the adhesive tape which was afterward wound around the cylinder (see left inset of Fig. 3) (thick line, this is one of the curves of Fig. 3) together with the previous measurements of the same sample performed on the flat substrate (dotted line — magnetic field applied perpendicularly, dashed line — in-plane field).

Finally, in Fig. 4, we show a comparison of the quasi-isotropic dependence shown in Fig. 3 with the dependences of Fig. 1 (of MLs deposited on the tape). We see that in the low field range magnetoresistance dependence measured on cylinder lies in-between those dependences obtained on flat surfaces and that the region of linear resistance changes is reduced in comparison to the curve of Fig. 1b. It should be noted that the in-plane magnetoresistance is isotropic in case of our $[Ni_{80}Fe_{20}/Au/Co/Au]_{10}$ MLs, too. However, the use of the cylinder shaped GMR sample gives the isotropic magnetoresistance effect even in the case of an arbitrary anisotropic in-plane GMR (for magnetic fields applied perpendicularly to the cylinder's axis).

4. Conclusions

We have shown that the giant magnetoresistance effect in $[Ni_{80}Fe_{20}(2\,nm)/Au(2\,nm)/Co(t_{Co})/Au(2\,nm)]_{10}$ MLs is compatible with the basic requirements of the flexible electronics. The amplitude of the effect is relatively high. We have demonstrated that the good bendability of GMR systems sputtered on adhesive tape can be utilized in magnetoresistance sensors. In particular, the cylindrically shaped GMR sensor can be exploited to reduce the effect of the intrinsic anisotropy of magnetoresistive sample. In that case the high bendability of the substrate allows to achieve a desired geometry of the sensor.

Acknowledgments

Supported by the Polish State Committee for Scientific Research, grant No. N507 287836.

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