The influence of Ru underlayer on magnetoresistive properties in bottom pinned spin-valves

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In this work, spin-valves with typical multilayer structure of Ta (10 nm) / Ru (x nm) / CoFe (3 nm) / IrMn (20 nm) / CoFe (3 nm) / Cu (3 nm) / CoFe (3 nm) / NiFe (5 nm) / Ta (5 nm) were fabricated with varying Ru thickness. In order to optimize the spin-valve magnetoresistive properties for sensors applications, the influence of the Ru underlayer thickness on the magnetoresistance (MR) ratio and the coercive field of the free layer was studied. It was shown that by using a Ru underlayer the MR ratio decreases, but it lowers the coercive field of the free layer, which is more advantageous for low-field sensor applications. By using the optimized thickness of the underlayer, an optimal MR of 3.45 % and a coercive field of 9 Oe were obtained.

(Received September 1, 2015; accepted February 10, 2016)

Keywords: Spin-valve, Giant magnetoresistance, Underlayer

1. Introduction

A typical giant magnetoresistive (GMR) structure consists of two ferromagnetic thin film layers separated by a non-magnetic conducting layer. In these multilayer structures, the electrical resistance depends on the relative orientation of the magnetization in the two ferromagnetic layers. The resistance of the multilayer structure is higher in the antiparallel configuration and lower in the parallel configuration. One of the most used GMR structures is the spin-valve, introduced for the first time in 1991 by B. Dieny [1]. In spin-valves, the magnetization direction of one ferromagnetic layer (the pinned layer) is pinned by exchange biasing with an antiferromagnetic layer while the magnetization direction of the second one (the free layer) can be changed by the application of a low external magnetic field. Therefore, the electrical resistance of the spin-valve can be changed by applying a low external magnetic field that alters the magnetization direction of the free layer.

For biomedical applications [2], [3], [4] that requires detection of the low magnetic fields created by magnetized nanoparticles, it is mandatory to obtain spin-valves with high MR ratio while maintaining the soft magnetic properties of the free layer. By carefully choosing the type and thickness of the underlayer, the MR properties of the spin-valves can be significantly enhanced, consequently the sensitivity of the spin valve sensor can be improved. In multilayered thin films, the nature of the underlayer influences the growth of the subsequent layers, thus it can affect the roughness, the preferential crystalline orientation and/or the grain sizes of the entire multilayer structure. It was shown that the MR ratio, the free layer coercive field and the exchange bias field are very sensitive to the nature of the underlayer [5], [6].

In this work we studied the influence of the Ru underlayer on the MR properties of a bottom pinned spin-valve with the aim of obtaining spin-valve sensors with suitable characteristics for magnetic nanoparticles detection. We show that by inserting a Ru underlayer in the spin-valve multilayer structure, the free layer coercive field can be decreased while minimally affecting the MR ratio and also the exchange bias field is significantly enhanced.

2. Experimental details

Spin-valve samples with the multilayer structure of: Si/SiO_2 / Ta (10 nm) / Ru (x nm) / CoFe (3 nm) / IrMn (20 nm) / CoFe (3 nm) / Cu (3 nm) / CoFe (3 nm) / NiFe (5 nm) / Ta (5 nm) were prepared by rf/dc magnetron sputtering using an ultra-high vacuum deposition machine. For the free layer, a CoFe/NiFe composite layer was used in order to benefit from the low coercive field of the NiFe layer and the relatively high MR ratio given by the CoFe. The ferromagnetic layers were deposited from sputtering targets with composition of $Co_{80}Fe_{20}$ and $Ni_{81}Fe_{19}$ and antiferromagnetic layer with $Ir_{22}Mn_{78}$ (composition is given in at. %). In order to study the influence of the Ru underlayer on the spin-valve magnetoresistive properties, the thickness of the Ru underlayer was varied from 0 to 10 nm. During deposition a magnetic field of 100 Oe was applied in the plane of the films, to induce the magnetic anisotropy in the pinned and free layers.

After deposition, the samples were annealed in a vacuum of 10^{-5} Torr for 1 h at a temperature of 270 ºC in order to improve the exchange bias coupling at the CoFe/IrMn/CoFe interfaces. During the annealing a magnetic field of 5 kOe was applied parallel to the field

direction during deposition. For characterization, the samples were diced into 5 mm × 5 mm square pieces. Current-in-plane MR measurements were carried out at room temperature using the four point probe measurement method with a driving current of 1 mA. During the measurements the magnetic field was applied parallel to the exchange bias direction. The minor hysteresis loops were obtained by vibrating sample magnetometer (VSM).

3. Results and discussion

Two spin-valve samples with Ta (10 nm) and Ta (10 nm)/ Ru (10 nm) underlayer were fabricated in order to study the effect of the nature of underlayer on the MR properties. Fig. 1(a) shows the MR curves for the spin valves with Ta (10 nm) and Ta (10 nm)/ Ru (10 nm) underlayer. The minor hysteresis curves are presented in Fig. 1(b) in order to clearly delineate the difference in coercivity of the free layer. It can be observed that the spin-valve sample with a 10 nm thick Ta underlayer shows an MR ratio of 3.85% and a free layer coercive field of 23 Oe, while the spin-valve sample with a Ta (10 nm)/ Ru (10 nm) underlayer shows an MR ratio of 2.25% and a coercive field of the free layer of 9 Oe. In addition, with the insertion of Ru layer it is observed that the exchange bias is significantly enhanced from 227 Oe to 288 Oe. The results here demonstrate that the underlayer can not only affect the magnetic properties of the pinned layer but also the free layer, indicating that the Ru layer insertion affects the microstructure of the entire multilayer structure.

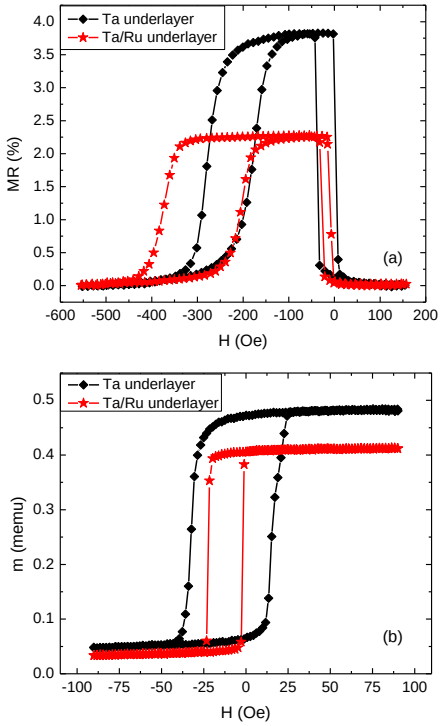

Fig. 1. Magnetoresistance curves (a) and minor hysteresis curves (b) measured for spin valves with different underlayer: Ta (10 nm) and Ta (10 nm) / Ru (10 nm).

The decrease of coercive field can be explained by the changes induced by the Ru underlayer in the microstructure (namely grain size and crystalline orientation) of layers above it including the free layer. Previously it was reported that in bilayers structures [7], [8], the magnetic properties of thin CoFe layers are dramatically affected by different underlayers. Several authors reported a decrease of the coercive field in CoFe thin films with Ru underlayers [9], [10], [11]. The authors had also observed that the microstructure of the CoFe layer can be significantly altered in terms of grain size and crystalline orientation. They suggest that the reason for obtaining lower coercive fields is the reduction of the grain size together with a change of the crystalline orientation.

We believe that the microstructural changes induced by growing the spin-valve on the Ru layer it is affecting the whole multilayer structure, this being the reason for the low coercive field of the free layer and also for the enhancement of the exchange bias field of the pinned layer.

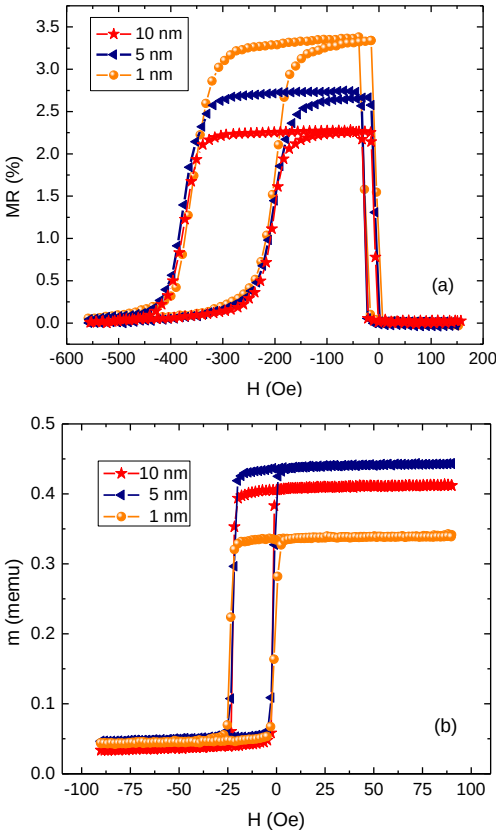

Fig. 2. Magnetoresistance curves (a) and minor hysteresis curves (b) measured for spin valves having different Ru thicknesses.

To further corroborate the effect of the Ru underlayer on the MR properties, spin-valves with decreased Ru thickness of 1 and 5 nm were investigated. Fig. 2(a) shows a comparison of the MR curves obtained for spin-valves having different thicknesses of Ru underlayer. The minor hysteresis curves are presented in Fig. 2(b). It was observed that by decreasing the thickness of the Ru layer,

the MR ratio increases while the coercive field value remains unchanged. Also, the exchange bias field seems to be independent of the Ru underlayer thickness.

Table 1. Magnetoresistive properties obtained for spin-valves having different Ru thicknesses.

Ru thickness (nm)	MR (%)	R (Ω)	H_c (Oe)	H_{eb} (Oe)
0	3.85	3.29	23	227
1	3.45	3.19	9	283
5	2.74	2.95	9	290
10	2.25	2.36	9	288

The MR properties obtained for spin valves having different thicknesses of the Ru underlayer are summarized in Table 1. For the spin valve with a 1 nm thick Ru underlayer a MR ratio of 3.45% and coercive field of 9 Oe were obtained. As can be observed, although the MR ratio is reduced by inserting a Ru underlayer its decrease can be minimized by using a very thin Ru layer while maintaining the low coercive field of the free layer. The decrease of the MR ratio by inserting a Ru layer and by increasing its thickness can be explained by the current shunting in the inactive part of the spin-valve. As the thickness of the Ru layer increases the resistance of the multilayer structure decreases (Table 1), creating a low resistance path which leads to a current shunting effect in the inactive part of the spin-valve and therefore leading to a decrease of the MR ratio.

4. Conclusions

The influence of the Ru underlayer thickness on the MR ratio and on the coercive field was studied. The optimum MR properties have been obtained for the spin-valve having a Ta (10 nm)/Ru (1 nm) underlayer. By using the optimized thickness of the underlayer, a MR ratio of 3.45 % and a coercive field of 9 Oe were obtained. It was shown that by using a Ru underlayer the MR ratio decreases, but it lowers the coercive field of the free layer.

Further investigation of the microstructural changes induced by the Ru underlayer insertion will be performed in order to provide a thorough understanding of the origin of the magnetic properties enhancement.

Acknowledgements

This work was supported by the European Commission in the framework of the Grant Agreement No. 316194 – NANOSENS, FP7-REGPOT-2012-2013-1 and by the Romanian Ministry of National Education and Scientific Research, project PN 02 02 (Contract No. PN 09 43) – NUCLEU Program. A. Jitariu acknowledges the financial support from the strategic grant POSDRU/159/1.5/S/133652, co-financed by the European Social Fund within the Sectorial Operational Program Human Resources Development 2007 – 2013.

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