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PARAMETERS CONTROL OF SOME SPIN VALVE GMR SENSORS WITH SYNTHETIC ANTIFERROMAGNETS

BY

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Abstract. A simulational analysis of a category of synthetic antiferromagnets (SAF) used in the spin valves for giant magnetoresistance (GMR) sensors was performed. Different structures of the stack of layers in the spin valve were considered in order to improve the strongly antiferromagnetic coupling between a pinned layer and a reference layer (Co hard magnetic alloys), across the spacer layer (Ru, Ta, Ti). Parametrical representations of the resistance-area product variation, ΔRA, and also of the areal storage density were given on graphs, using theoretical considerations and 3D structural simulations performed with the HFSS program. Internal phenomena were considered and also the influence of the external fields. A controlled structure can be obtained, our results indicating a GMR ratio of about 1.3...2.2%, respectively a variation of the resistance-area product of 0.4...16 $m\Omega\cdot\mu m^2$, for an inter-layer thicknesses of 1...1.2 nm, in an applied field of about 2...6 k Oe. Results are dependent of the stack structure, the role on each intermediate exchange layer being essential in the process of performances improving.

Keywords: spin valve; giant magnetoresistence; resistance-area product variation; structural simulation; maxima; parametric analysis.

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1. Introduction

A simulational analysis of a category of synthetic antiferromagnets (SAF) used in the spin valves for GMR sensors was performed in this paper.

Among the applications of the spin-valve structures, electric and electronic devices were manufactured, like: magnetic read heads, magnetic field sensors and GMR (giant magnetoresistance) isolators, microelectromechanical systems (MEMS) and other devices (Hartmann, 2013; Hirota *et al.*, 2013). The magnetic field sensors represent a category of interest, being devices used to read data in hard disk drives, or like biosensors, etc.

The layered structures of alternating ferromagnetic and non-magnetic conductive thin films present GMR effect for peculiar sets of materials in contact. If the nature and geometrical parameters of the layers are properly chosen, the quantum mechanical effect can be controlled and performances of the structures are satisfactory for different technical applications. These structures are also used for data storage in the magnetoresistive random-access memories and in the racetrack memories as read heads, as well.

Due to the properties of these material structures, the areal storage densities were increased significantly by using the spin-valve read heads for receiving the information (the bits of data). These read heads replace successfully the thin film inductive heads, and ensure superior performances. In particular, the magnetoresistive ratio, $\Delta R/R$, in the case of layered structures with tunneling effect can reach values of a few percents, having as consequences lower dimensions at device level and high storage density.

2. Characterization of the Spin Valves

Different structures of the stack of layers in the spin valve were considered in order to improve the strongly antiferromagnetic coupling between a pinned and a reference layer, across the spacer layer. Hard magnetic layers based on Co alloys have been analyzed, with a inter-layer of Ru, Ta, Ti and a non-magnetic spacer between the reference and free layers of Cu or alternative.

A parallel sensing current flows in the plan of layers, parallel with the interfaces, in the Current-In-Plane (CIP) geometry. The current density is non-uniform, in layers of different nature but with the same thickness being larger in the layer with lower resistivity (Hartmann, 2013). This is due to the fact that in these cases the free-paths, λ (the average distances along which an electron diffuses between scattering events) are different.

In the considered GMR spin valve, the succession of layers can be described as follows, from above to bottom (Fig. 1):

– the soft magnetic layer (free layer), material: Co_2MnSi, Co_2CuSn, $Co_2FeAl_{0.5}Si_{0.5}$ (Heusler alloys), thickness: 5-10 nm, placed on top, presenting free oriented magnetization;

– the spacer, Cu alloy, + Pt (6-8%) or Ni (13-15%), thickness: 2-4 nm, non-magnetic, with role of exchange decoupler between the magnetic layers;

– the reference layer, material: the same Heusler alloys, thickness: 12 - 25 nm;

– the inter-layer, Ru, Ta, Ti respectively, heavy metal, thickness: 1-2 nm, where intense exchange interactions occurs;

– the hard magnetic layer (pinned layer), the same Heusler alloys, thickness: 20-30 nm, placed on the bottom of the stack, presenting fixed magnetization;

– the substrate, an oxide, MgO (001), NiO, is a pinning layer, antiferromagnetic, fixes the magnetization of the bottom hard magnetic layer and raises its coercivity.

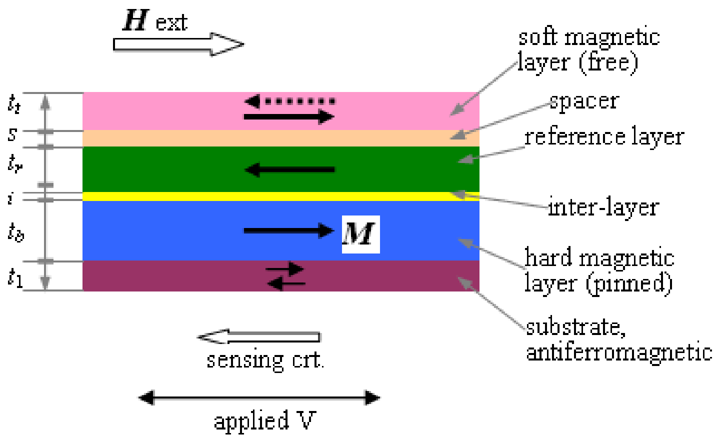

Fig. 1 – The layered structure of the GMR spin valve. The current flows in the layer planes (CIP geometry).

The theoretical support of the oscillatory antiferromagnetic coupling of the magnetic layers in the stack was considered the RKKY (Ruderman-Kittel-Kasuya-Yosida) theory and the quantum well models. The intensity of the antiferromagnetic coupling depends strongly on the nonmagnetic spacer, the dependence being even periodical.

The GMR ratio in the spin valve can be defined as (Hartmann, 2013):

$$\frac{\Delta R}{R_0} = \frac{\Delta R_{\max}}{R_0}\left[\frac{1-\cos(\theta_2-\theta_1)}{2}\right] \tag{1}$$

where θ_1 and θ_2 are the magnetization orientation angle of the pinned and free FM layers in the spin valve, respectively.

In contrast, the AMR ratio is (Park *et al.*, 2011; Tang, 2007):

$$\frac{\Delta\rho}{\rho_0} = \frac{\Delta\rho_{\max}}{\rho_0} \cdot \cos^2\theta \tag{2}$$

where θ = angle between the current and magnetization.

For obtaining the results used for structure optimization, another formula has been applied for estimating the GMR of the considered spin valves, using the sensing current which transforms the change in resistance in a readback voltage, given by simulation:

$$\frac{dR}{R} = \frac{R(H) - R(0)}{R(0)} \tag{3}$$

where $R(H)$ is the resistance of the sample in a magnetic field H, and $R(0)$ is the resistance in null field.

The specific resistance has been computed, AR = the product of the area A through which an assumed uniform CPP current flows and the sample resistance R. The difference between the anti-parallel and parallel states (magnetizations of adjacent ferromagnetic layers in the stack) leads us to the specific resistance variation: $\Delta AR = AR_{anti\|} - AR_{\|}$.

Considering these formula, the CIP magnetoresistence ratio can be defined as: $MR_{\mathrm{CIP}} = \Delta AR/AR_{\|}$, respectively in percents (Yuasa and Djayaprawira, 2007):

$$MR_{\mathrm{CIP}}[\%] = \frac{\Delta AR}{AR_{\|}} \tag{4}$$

with the notations used above.

3. Results for the Specific Resistance Variation

A parametrical representation of the resistance-area product variation, ΔRA, was given on graphs, using theoretical considerations and 3D structural simulations performed with the HFSS program. The simulation strategy was conceived considering in the first place the spin valve performances dependence on the properties of the hard magnetic alloy. Internal phenomena were considered and also the influence of the external fields.

A 3D simulational set up was realized in order to reproduce the stack of layers in the spin valve structure, focusing on the spin-orbit coupling modification, induced by geometrical parameters variation under the applied field.

The GMR ratio in function of the spacer layer thickness correlated with the pinned layer thickness was calculated using the formula (3). In the same time, the $\Delta R/R$ evolutions in function of the average grain size in the ferromagnetic layer and the applied magnetic field have been also considered.

Our target was determination of the resistance-area product variation, ΔRA, for the considered read head spin valve in function of spacer thickness s, for different inter-layer thicknesses i. Results have been represented on the parametrical graphs in Fig. 2.

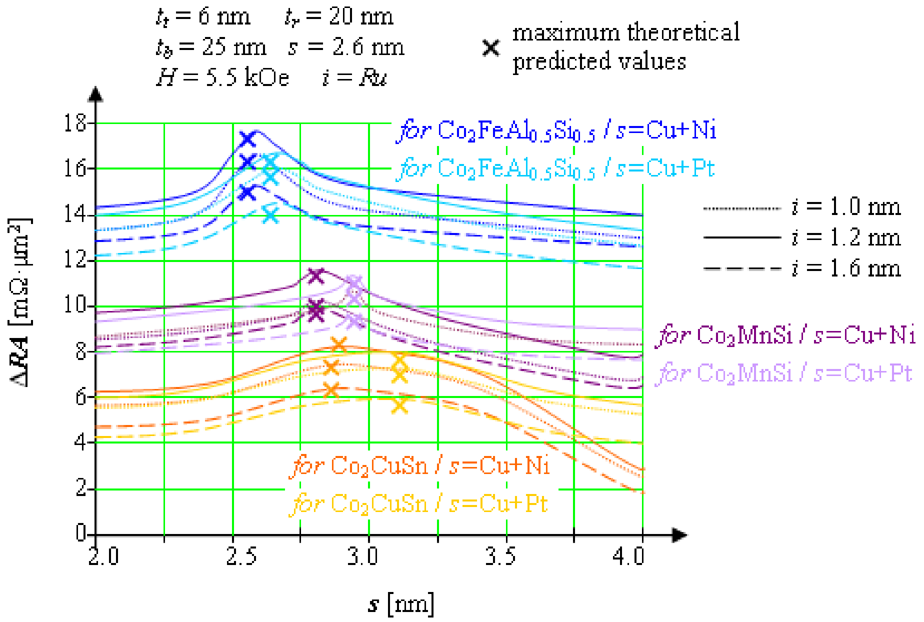

Fig. 2 − Specific resistance variation in function of spacer thickness, for the considered combination of materials in the spin valve GMR sensors. The theoretical predicted values of the ΔRA maximum are indicated on graphs.

One observes a slow increasing and than a decreasing evolution of the ΔRA with s, with a wide maximum, which is more wide and flat then magnetic material magnetization is lower. When the *s* values corresponding to the maximum are transcended, greater the s, weaker the interlayer interactions and weaker the MR. In practice, this effect is more acute due also to the current shunting effects which occur when electrons preferentially flow through the thicker spacer instead of undergoing scattering at the magnetic layer/spacer interfaces (Hartmann, 2013; Covingtona *et al*., 2001).

Specific resistance variation presents a maximum determined by combined effects like the hysteresis phenomenon (the maximum magnitude depends on value of the hysteresis magnetization – field) and the defects at interfaces level. The pinhole defects degrade significantly the MR due to the direct interactions between the magnetic layers, the effect which is also more acute in practice (Hirota *et al*., 2013).

In order to determine the performances of the considered spin valve GMR sensors, we have determined the variation of the resistance-area product (ΔRA, [m$\Omega\cdot\mu$m^2]) of read head spin valve in function of spin diffusion length l_{sf}, [nm], which is in our case of tens of nm order for the spin valves with Heusler alloys.

Variation of the resistance-area product (ΔRA, [m$\Omega\cdot\mu$m^2]) of read head spin valves in function of reference layer thickness [nm] have also been determined considering the intense electron scattering phenomena occurring in this layer and the tunneling effects.

Using and combining the results, we have determined and represented on graphs (Fig. 3) the parametrical evolution of the areal storage density at spin valve level, for a continuous modification of the specific resistance variation, in the case of the considered hard magnetic materials (Heusler alloys) in the spin valve GMR sensors.

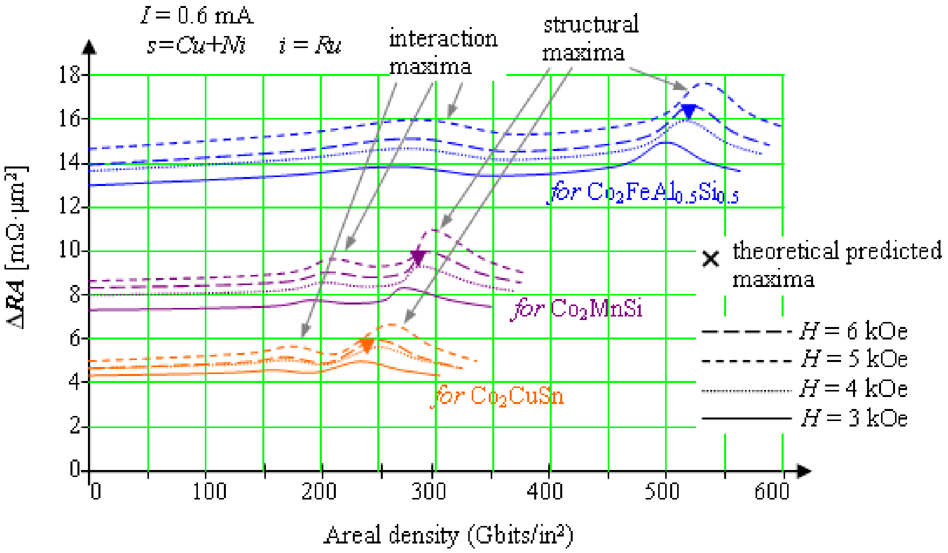

Fig. 3 − Evolution of the areal density for a continuous modification of the specific resistance variation, for the considered hard magnetic materials in the spin valve GMR sensors. Structural, respectively interaction maxima of the ΔRA, present in different domains of the areal density values, are indicated on graphs.

Variations of the resistance-area product ΔRA, [m$\Omega\cdot\mu$m^2] of a few units are characteristic for the considered hard magnetic materials in the read head spin valve, when the areal density evolves up to 300 Gbit/in^2, respectively 500 Gbit/in^2

for different alloy nature, as we have indicated on graphs. Evolutions for some specific sub-domains present maxima, which can be characterized like structural and interaction maxima.

The main structural maximum of the specific resistance variation, present on each graph, is imposed by the magnetic ion in the hard magnetic alloy of Heusler type. The maximum characteristics depend on the internal interactions in the exchange coupled system, hard - soft magnetic. If the alloy structure changes, the maximum shifts consistently and also its magnitude modifies.

For each type of magnetic material, interaction maxima occurs, generally less intense than the structural maximum. These maxima are present for materials with a common magnetic ion (Co in our case), and are controlled by other factors, like the resonant coupling phenomena between structure, external field H_{ext} and the sensing current I.

The magnitude of the maxima is imposed finally on the spin current, the magnetization dynamics being determined by the torques moving the spins, torques generated by the exchange interaction between conduction electrons and domain wall magnetizations, under the H_{ext} influence. Superior performances of the spin valve GMR sensors can be achieved by correlation of the magnetic material nature and geometrical parameters of the reference layer and inter-layer in the spin valve.

4. Discussions and Conclusions

A controlled structure of the spin valve can be obtained, using the parameters dependence determined by simulation. A lot of parameters characterizing the spin valve structure are implied, like magnetic and non-magnetic materials nature, layer thicknesses, grain sizes in the magnetic alloys, spin diffusion length and defect rates, but not only.

A discussion of the phenomena based on the simulation results can be opened. Among the conclusions, one can formulate the followings.

The maxima of the specific resistance variation, ΔRA, depend on the hysteresis phenomenon inside the magnetic material and at structure level and also by the defects at interface level.

The areal storage density evolves when ΔRA varies in the domain of interest corresponding to the superior values of the MR ratio obtained for the analyzed structures by parameters correlation. Structural and interaction maxima are present on graphs, which are function of the hard magnetic alloy nature and depend on the coupling between substance and field. Phenomenologically speaking, the maxima magnitude is dependent on the spin current flowing in the spin valve layers.

The obtained results have indicated us a GMR ratio of about 1.3...2.2%, respectively a variation of the resistance-area product of 0.4...16 $\text{m}\Omega\cdot\mu\text{m}^2$, with maxima in the last third of the scale, for an inter-layer thicknesses of 1...1.2 nm, in an applied field of about 2...6 k Oe. The results are dependent of the stack structure in the spin valve, the role on each intermediate exchange layer being essential in the process of performances improving.

REFERENCES

Covingtona M., Rebei A., Parker G.J., Seigler M.A., *Spin Momentum Transfer in Current Perpendicular to the Plane Spin Valves*, Fujitsu Sci. Tech. J., **37**, *2*, 174-182 (2001).

Hartmann U., *Magnetic Multilayers and Giant Magnetoresistance: Fundamentals and Industrial Applications*, Springer Science & Business Media, 2013.

Hirota E., Sakakima H., Inomata K., *Giant Magneto-Resistance Devices*, Springer Science & Business Media, 2013

Park B.G., Wunderlich J., Martí X., Holý V., Kurosaki Y., Yamada M., Yamamoto H., Nishide A., Hayakawa J., Takahashi H., Shick A.B., Jungwirth T., *A Spin-Valve-Like Magnetoresistance of an Antiferromagnet-Based Tunnel Junction*, Nat. Mater., **10**, *5*, 347-351 (2011).

Tang X., *Magnetotransport and Magnetization Reversal of Electrodeposited Multilayer Nanowires*, Thesis, Rensselaer Polytechnic Institute, Troy, New York, Pro Quest Information and Learning Company, UMI Microform 3286344, 2007.

Yuasa S., Djayaprawira D.D., *Giant Tunnel Magnetoresistance in Magnetic Tunnel Junctions with a Crystalline MgO(0 0 1) Barrier*, J. Phys. D: Appl. Phys., **40**, R337–R354 (2007).

CONTROLUL PARAMETRILOR UNOR SENZORI GMR CU VALVE DE SPIN PE BAZĂ DE ANTIFEROMAGNEȚI SINTETICI

(Rezumat)

A fost realizată o analiză simulațională a unei categorii particulare de antiferomagneți sintetici (AFS), utilizați la valvele de spin pentru senzorii GMR. Au fost considerate diferite structuri ale stivei de straturi în valva de spin, în scopul îmbunătățirii cuplajului antiferimagnetic puternic dintre stratul cu magnetizație fixată şi stratul de referință (fabricate din aliaje magnetice dure de Co de tip Heusler), prin intermediul unui strat subțire separator (Ru, Ta, Ti). Au fost redate grafic reprezentări parametrice ale variației produsului rezistență - arie, Δ*RA*, precum şi ale densității areale de stocare a biților, obținute pe baza considerațiilor teoretice şi a simulărilor structurale folosind programul HFSS (tehnologie Ansoft). În cadrul modelului de simulare au fost considerate fenomenele interne şi totodată influența câmpurilor externe. Se poate obține astfel o structură controlată, rezultatele noastre indicându-ne un raport MRG de circa 1.3...2.2%, pentru grosimi ale stratului separator de 0.8...1.2 nm, pentru o valoare a câmpului aplicat de circa 6...8 k Oe. Rezultatele depind de structura stivei, rolul fiecărui strat intermediar la nivelul căruia se manifestă interacțiuni de schimb fiind esențial în procesul de îmbunătățire a performațelor structurii.