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AREAL DENSITY OPTIMIZATION AT PERPENDICULAR RECORDING USING PARTICULAR SPIN VALVE HEADS

BY

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Abstract. A a category of metallic spin valves for read heads presenting colosal magnetoresistance changing have been analyzed by simulation methods, using the 3D HFSS program. Hard ferromagnetic alloys were considered in the stack of the nanometric magnetic/spacer/magnetic layers, based on Fe and Co and a proper spacer, working in the current-perpendicular-to-plane (CPP) mode. The magnetoresitance changes (*MR*, [%]) were calculated by theory and from simulation data, under different condition of exploitation, in function of the thickness of the hard magnetic layer and spacer, average grain size, and applied field respectively. Results indicate us monotone evolutions for some specific sub-domains and present maxima when the structure parameters can be correlated. A magnetoresistance ratio of about 0.4...2% have been computed, dependent on layers nature and thickness, for the alloy grain sizes up to 7-8 nm and an applied field of 2-10 kOe. Data were used for obtaining high resolution reading performances, which to overcome the reported results.

Keywords: magnetoresistance; spin valve; thin film; spin current; areal density.

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1. Introduction

A category of metallic spin valves for read heads presenting colossal magnetoresistance changing have been analyzed by simulation methods, using the 3D HFSS program by Ansoft.

The read heads explore the bits traveling through the recording media (the disk surface). In the case of the perpendicular recording, the bits point up or down perpendicular to the disk surface, in comparison with the parallel recording case, where the bits are moving in the disk plane (Jogo *et al*., 2007; Nagasaka *et al*., 2006). Higher fields are necessary at perpendicular recording to set the magnetization, but the advantage is that the magnetization is more stable.

The ultrahigh-density recording with areal densities over hundreds of Gb/in^2, can be achieved by exploiting the properties of the tunnel magnetoresistive (TMR) heads (Tanaka *et al*., 2002) implemented into the spin valves for read heads. A few structures of this type have been analyzed in this paper and their properties have been determined in order to correlate the parameters to optimize the structure.

2. Characterization of the Spin Valve Materials

Hard ferromagnetic metallic alloys have been considered in the spin valves, based on Fe and Co and a proper spacer, working in the current-perpendicular-to-plane (CPP) mode (Fig. 1).

The stack of layers was considered as follows (from top to bottom):

– a soft magnetic layer, on top of the stack - the free layer, with free oriented magnetization. Materials were chosen like Co_2MnSi, Co_2CuSn (Heusler alloys) or NiFeCo, with thicknesses of 5...10 nm.

– a spacer layer, of Cu alloy, + Pt (8%), Ni (14%), with thicknesses of 2...4 nm. This represents a non-magnetic spacer, with role of exchange decoupler between the magnetic layers.

– a reference layer, with the same nature like the soft layer: Heusler alloys or NiFeCo, with thicknesses of 12...25 nm

– a inter-layer, of Ru (a heavy metal), with thicknesses of 1...2 nm, the finer layer, where the most of the exchange interactions occurs

– a hard magnetic layer, which is the pinned layer, with fixed direction of the magnetization. The same Heusler alloys of NiFeCo were considered for this layer, with thicknesses of 20...30 nm. The layer is placed at the basis of the stack, on a substrate which maintains its magnetization direction.

– a substrate, represented by an oxide, MgO (001) or NiO. This is the pinning layer, antiferromagnetic, which fixes the bottom layer magnetization and raises its coercivity.

The current-perpendicular-to-plane (CPP) geometry was chosen, where the sensing current flows perpendicular to the layers.

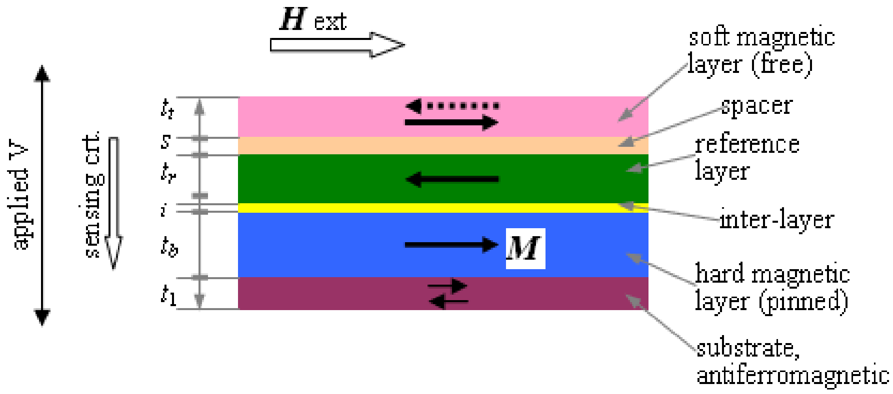

Fig. 1 − The considered layers configuration in the spin valve head. Sensing current flows perpendicular to the ferro / nonferro-magnetic interfaces, in the current-perpendicular-to-plane (CPP) geometry.

The spin valve working in this geometry presents a greater magnetoresistance ratio δ_H, which ensures a greater sensitivity to the device than in the case of the parallel geometry. The theoretical model was based on the Valet-Fert theory (Valet and Fert, 1993) - the theory for giant magnetoresistance (GMR) in the spin valves with CPP geometry. The current which is passed perpendicular to the ferro / nonferro-magnetic interfaces it is assumed that presents an uniform current density uniform across the area. The electronic transport in magnetic multilayers depends on the electrons scattering phenomena due to the spin-orbit interactions.

An important parameter considered at simulations was the spin-diffusion lengths l_{sf}, which represents the average distance over which the electrons diffuses between the spin-relaxation events and it is linked by the losses. These events are more rare in comparison with the electron scattering events which occurs at current passing through the stack of layers.

In a spin valve, the perpendicular magnetoresistance ratio can be computed with the formula (Bass, 2013):

$$\rho = \sum_{i=1}^{n} \left(\frac{1-\cos\phi_i}{2} \right)_i \tag{1}$$

where $\Phi_i = \theta_{\mathrm{bottom},i} - \theta_{\mathrm{top},i}$ is the difference in the magnetization angle between a grain from the bottom hard magnetic layer and a grain in the adjacent reference layer, n = total number of grains. The presence of a percentage of structural defects was taken into account at simulation.

For estimating the MR of the considered spin valves using the simulation data, another formula has been applied, using the sensing current which transforms the change in resistance in a readback voltage (Hirota *et al*., 2013; Sharma, 2009), given by simulation:

$$\frac{dR}{R} = \frac{R(H) - R(0)}{R(0)} \tag{2}$$

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, AR represents the product of the area A through which an uniform CPP current flows and the sample resistance R. Variation of this parameter is $\Delta AR = AR_{anti\parallel} - AR_{\parallel}$, which represents the difference between the specific resistances in the anti-parallel and parallel states (magnetizations of adjacent ferromagnetic layers in the stack) (Hirota *et al*., 2013; Rychkov *et al*., 2009). On the context, the CPP magnetoresistance ratio was considered as:

$$MR_{\text{CPP}}[\%] = \frac{\Delta AR}{AR_{anti\parallel}} \tag{3}$$

3. Results for Magnetoresitance Changes

For the considered magnetic materials in the spin valve (Co_2MnSi, Co_2CuSn or NiFeCo), the magnetoresitance changes (*MR*, [%]) were calculated by theory and from simulation data, under different condition of exploitation.

Dependence of the *MR*, [%] on physical and geometrical parameters of the successions of nanometric magnetic/spacer/magnetic (anti-parallel magnetized) layers have been determined and represented on graphs. A sense current, *I*, of 0...3 mA has been considered in the stack.

Parametrical representations of the magnetoresistance ratio on thickness of the hard magnetic layer and spacer, average grain size, and applied field respectively, indicate us monotone evolutions for some specific sub-domains and present maxima which are of interest in practice. In order to obtain better results in material exploitation, we have focused on correlation of the parameters which ensure a maximal response of the structure (spin valve read head), on the basis of simulation results.

The CPP magnetoresistance ratio of the considered spin valves in function of the average grain size of the hard magnetic layer was given in Fig. 2.

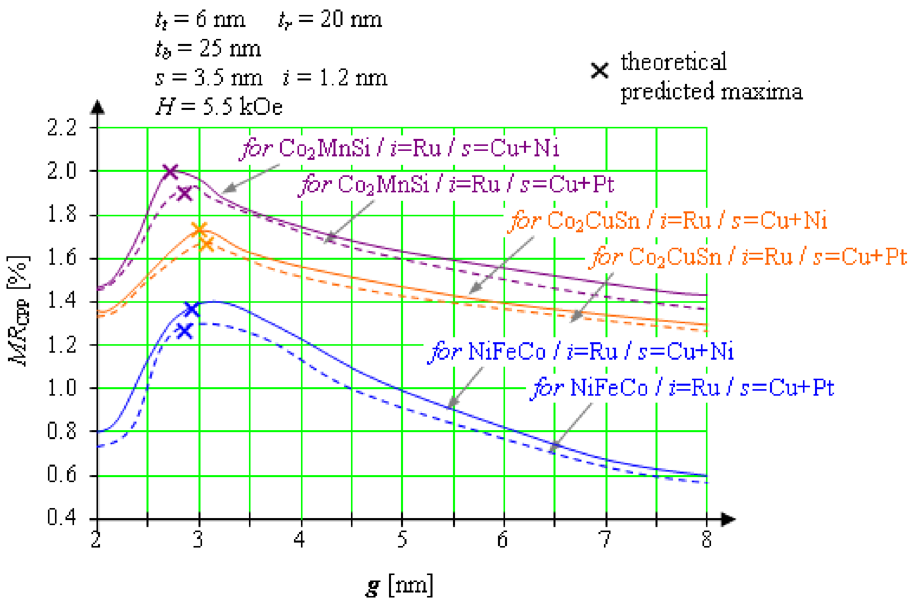

Fig. 2 − The CPP magnetoresistance ratio of the considered spin valves in function of the average grain size of the hard magnetic layer. Simulational and theoretical maxima were illustrated on graphs.

Simulations have indicated us that the interlayer exchange coupling field decreases when the hard layer thickness increases. Coupling depends on grain sizes, consequently smaller grains are equivalent with a higher magnetoresistance. *MR* dependence on *g* is resonant, the maximum occurring also at lower values for *g* in the hard magnetic material.

Theoretical predicted maxima are of lower magnitude and slightly shifted in respect with simulational maxima, due to the fact that the theoretical model do not take into account all the influences and parameters interdependence considered in the simulations, from the lattice level to grains, interfaces and thin film level.

The CPP magnetoresistance ratio for the considered magnetic materials in the spin valves in function of the applied magnetic field ***H*** was illustrated in Fig. 3. For clarity reason, we have focused on the curves corresponding to the higher magnitude of the maximum, when spacer / inter-layer thickness varies, which were illustrated on graphs for each material.

Change in magnetoresistance presents resonant evolutions in function of the field, the maximum which characterizes the interaction (magnetization - spins − field) being high and sharp. One can conclude that the device operation out of maximum area is not of interest in practice. The maximum position has to be determined and simulation offers a non-destructive reliable method.

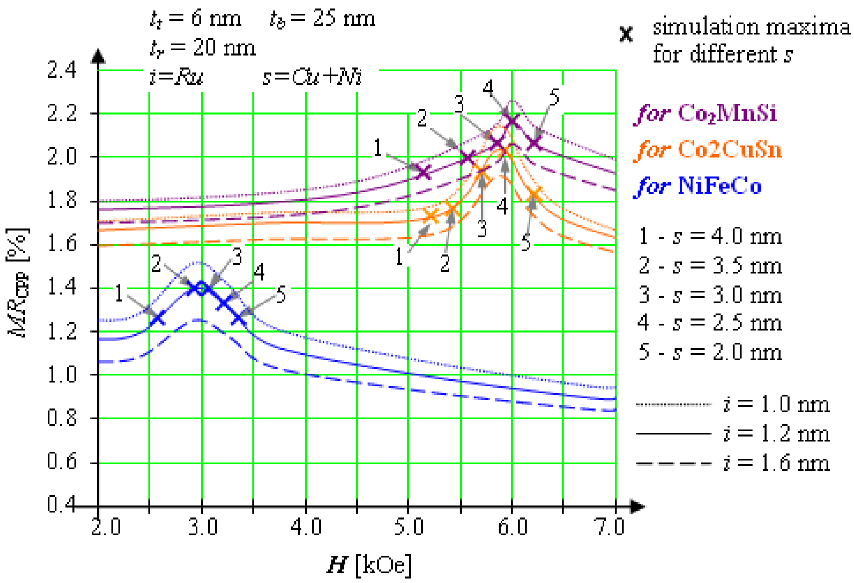

Fig. 3 − The CPP magnetoresistance ratio of the considered hard magnetic materials in the spin valves in function of the applied magnetic field *H*. Curves corresponding to the higher magnitude of the maximum, when spacer / inter-layer thickness varies, were illustrated on graphs for each material.

The simulations have also indicated that, for a given hard magnetic material, spacer nature imposes the magnitude report of the maxima for different curves.

The changes in the CPP magnetoresistance ratio in function of the spacer layer thickness *s*, for the considered combinations of materials in the spin valve, are given in Fig. 4. The *MR* ratio presents an increasing and than a decreasing with *s*, with a wide maximum, which is more wide and flat then magnetic material magnetization is lower. If the spacer thickness has greater values than the value corresponding to the *MR* ratio maximum, greater is the *s*, weaker the interlayer interactions and weaker the *MR*.

We have also to consider the presence of current shunting effects, when electrons preferentially flow through the thicker spacer instead of undergoing scattering at the magnetic layer/spacer interfaces. This determines in practice a slight decreasing of the *MR* ratio values, no more than a few percents.

Our studies, based on physical considerations (Bass, 2013; Eid *et al.*, 2002), use the simulational parametrical analysis for explaining the *MR* ratio maximum causes: the hysteresis phenomenon (maximum magnitude depends on the value of the hysteresis magnetization – field); the presence of defects, in particular of the Pinhole defects, which degrade significantly the *MR* due to the direct interactions between the magnetic layers.

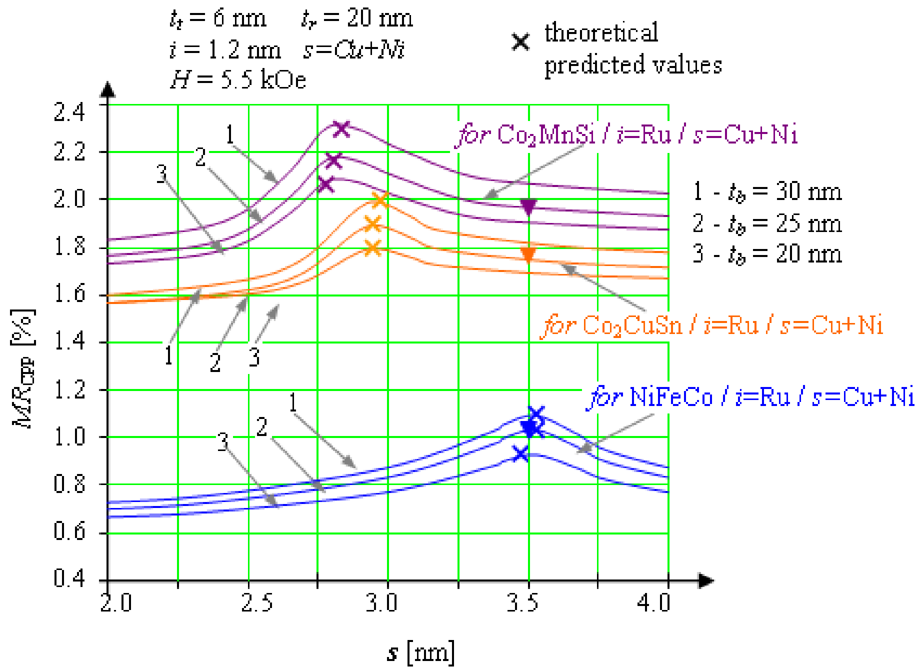

Fig. 4 − The CPP magnetoresistance ratio of the considered hard magnetic materials in the spin valves in function of the spacer layer thickness *s*, for the considered combinations of materials in the spin valve. Theoretical predicted maxima were indicated on graphs.

As a conclusion of our study, the areal density of hard disk drives in function of the CPP magnetoresistance ratio of the considered spin valves was represented in Fig. 5. The presence of groups of single and multiple maxima can be noticed on graphs.

The main structural maxima of the areal density are imposed by the magnetic ion in the hard magnetic alloy and their characteristics depend on the internal interactions in the exchange coupled system, hard - soft magnetic. A few interaction maxima, generally less intense, are controlled by other factors, like the resonant coupling phenomena between structure, external field and sensing current.

By modifying different parameters of the structure, maxima with magnitude depending on the spin current were identified. Their originate in the magnetization dynamics, which is determined by the torques moving the spins, torques generated by the exchange interaction between conduction electrons and DW magnetizations, under the influence of external magnetic filed.

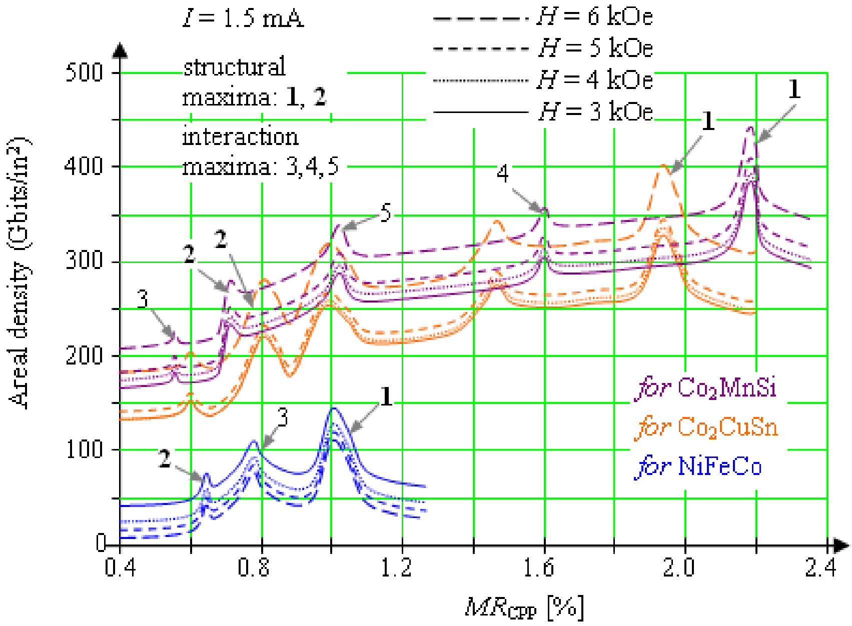

Fig. 5 − Areal density of hard disk drives in function of the CPP magnetoresistance ratio of the considered spin valves. Structural, respectively interaction maxima were illustrated on graph.

4. Structure Optimization and Conclusions

A set of new magnetic materials (& Heusler alloys) have been considered in this paper, placed in a nano-layered structure inside a spin valve for read heads. The advantages of such a kind of structures for specific applications were illustrated, when the structure parameters can be correlated using the results given by the 3D structural simulation.

For the considered spin valve structures we have computed a magnetoresistance ratio of about 0.4...2.2%, dependent on the magnetic/spacer layers nature and thickness, for alloy grain sizes up to 7-8 nm and an applied field of 2-10 kOe.

For ultrahigh-density recording, an areal density of a few hundred of Gb/in^2 was found, with maxima depending on the magnetoresistance changes at structure level. Our purpose was the parameter correlations in order to obtain maxima of the magnetoresistance ratio associated with a maximal areal density, for high resolution reading performances, which to overcome the results reported until now.

Our simulational data have been able to indicate solutions for a better response of the considered spin valves in the subdomains of parametrical computed maxima. The set of parameters of interest can be extracted from graphs represented on the basis of simulation results and generates the structure implementation.

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OPTIMIZAREA DENSITĂȚII DE STOCARE PE SUPRAFAȚĂ ÎN MODUL PERPENDICULAR FOLOSIND CAPURI DE ÎNREGISTRARE PARTICULARE CU VALVĂ DE SPIN

(Rezumat)

A fost analizată prin metode de simulare o categorie de valve de spin metalice prezentând magnetorezistență gigant, folosite pentru capuri de citire, cu ajutorul programului 3D HFSS. În stiva de straturi nanometrice magnetic/separator/magnetic au fost considerate aliaje feromagmetice de înaltă rezistivitate pe bază de Fe, Co şi Al, cu un material potrivit ca strat separator, funcționând în modul de operare curent-perpendicular-pe-plan (CPP). Modificările de magnetorezitență (ΔR) au fost calculate din considerente teoretice şi în paralel cu ajutorul datelor obținute prin simulare, în diferite condiții de exploatare, funcție de grosimea stratului magnetic dur şi a separatorului, de dimensiunea grăunților cristalini şi respectiv de câmpul aplicat. Rezultatele ne indică evoluții monotone pentru unele subdomenii specifice şi prezintă maxime când parametrii structurali pot fi corelați. A fost calculat un raport al magnetorezistenței (*MR*) de circa 0.4...1.7%, dependent de natura şi grosimea straturilor, pentru dimensiuni ale graunților cristalini ai aliajului de pâna la 7-8 nm şi un câmp aplicat de 2-10 kOe. Datele au fost folosite pentru obținerea unei proces de citire performantă de înaltă rezoluție a datelor, cu rezultate superioare celor raportate până în prezent.