Comparison of computed amplitudes of magnetoresistance in spin-valve structures with wafer probe measurements

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Abstract : **A code has been developed based on the semi-classical theory of giant magnetoresistance of Camley and Barnas [1]. It computes the sheet conductance and magnetoresistance of spin-valve structures. The input parameters are phenomenological transport parameters (mean-free paths and reflection/transmission coefficients at interfaces). These parameters are fairly well known in most conventional materials. Several refinements have been introduced into the initial theory, in particular spin-intermixing due to magnon scattering, anisotropy in mean-free paths, and angular dependence of transmission through the interfaces. A few examples of the use of this code are described in this paper. Such code could be used as a guideline in the optimization of spin-valves.**

Index terms- spin-valves, semi-classical theory of giant magnetoresistance.

I. INTRODUCTION

The increase in areal density of magnetic recording disks to larger than 10Gbit/inch^2, will require new types of thin film heads having larger sensitivity than the conventional magnetoresistive (AMR) heads. Spin-valve structures [2] are one of the promising candidates for this purpose. The two main advantages of spin-valves are i) their large magnetoresistance amplitude even with a thin sensing layer, and ii) the intrinsic linearity of the spin-valve response. Point i) becomes a significant advantage at high areal density since the amount of magnetic flux entering the magnetoresistive (MR) element from the disk decreases with the size of the bit cell. For a given amount of magnetic flux, larger rotation of the sensing layer can be achieved if the thickness of this layer is smaller. Compared to AMR heads, point ii) implies spin-valve heads can use a larger portion of the MR response, while generating smaller harmonics in the output signal. Several prototypes of spin-valve heads performing at areal density above 5Gbit/inch^2 have already been presented [3-5].

From a materials point of view, much research focuses on the optimization of the magnetoresistive properties of spin-valves (optimization of thicknesses, dusting of the interfaces by a third element to improve the GMR amplitude and the structural stability upon annealing, confinement of the spin-valve between insulating layers to increase the specular reflection of conduction electrons on outer surfaces, etc).

From a theoretical point of view, two classes of theories have been put forward to explain the GMR phenomenon. The first class describes the conduction electrons as a free electron gas submitted to spin-dependent scattering potentials at the interfaces and/or in the bulk of the ferromagnetic layers [6]. This model is treated either within a semi-classical [1,7,8] or a quantum statistical approach [9]. The second class of theories focuses on the electronic band matching effect. It has been used mainly to interpret the GMR of Fe/Cr or Co/Cu type multilayers [10-12].

In this paper, we present a code that we have developed to compute the sheet conductance and magnetoresistance of spin-valve structures at any temperature up to approximately 400K. This code is based on the solution of the Boltzmann transport equation. It is an extension of Camley and Barnas theory [1], which includes several refinements. Several groups have successfully used this approach to, at least semi-quantitatively, interpret the transport properties (conductance and magnetoresistance *simultaneously*) of spin-valve structures [8,13,14]. The code establishes a bridge between the macroscopic measurable quantities (resistance and magnetoresistance) and the microscopic parameters of the spin-valves such as the spin-dependent mean-free paths of conduction electrons and the reflection/transmission coefficients at the various interfaces or at the outer surfaces. These parameters are considered in a phenomenological way. Our goal is not to calculate them from electronic band structure calculation as some theories do [10-12]. Orders of magnitude of these microscopic parameters are now fairly well known in most commonly used materials. These parameters can be further adjusted by fitting experimental data (R and $\Delta R/R$) on series of samples consisting of a single elements and spin-valves. Once the microscopic parameters have been determined, the code can be used in a predictive way as a guideline for the optimization of spin-valve structures.

II. CODE

A detailed description of the semi-classical theory used in the code can be found in [15]. However, several refinements have been introduced in the initial theory [1] :
-Both interfacial and bulk spin-dependent scattering are taken into account.

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-The dependence of the transmission coefficients through the interfaces on the angle of incidence of the electrons is taken into account[16].
-An anisotropy in the mean-free path due to scattering at grain boundaries is taken into account [8]. This anisotropy results from the columnar texture of sputtered spin-valves. The dependence of the grain size on the film thickness and its consequence on the scattering rates at grain boundaries has been considered by Rijks [14]. This dependence can also be taken into account.
-Potential barriers between adjacent layers can be introduced. The barriers result from a mismatch in the electronic band structure of adjacent metals. We did not consider these potential steps because in most experimental situations, they should lead to anomalies in the angular variation of the spin-valve magnetoresistance that are not observed [17].
-Partial or total specular reflection of electrons on the outer boundaries is taken into account.
-Spin ↑ and ↓ intermixing due to magnon scattering has been introduced following the approach of Duvail, et al. [18]. This effect is unimportant at low temperature but plays a significant role at room temperature and above [19].

III. EXAMPLES OF USE OF THE CODE

A few examples can already been found in the literature:
-In references [8,19.20], simultaneous fits of the sheet conductance and magnetoresistance of series of F t_F/NM t_{NM}/NiFe 50Å/FeMn 80Å/Cu 15Å spin valves with F=$Ni_{80}Fe_{20}$, Co or Fe, t_F varying between 20 and 430Å, NM=Cu or Au, t_{NM} varying between 16 and 90Å, were performed. These studies provided sets of parameters for the mean-free paths in these various sputtered materials and spin-dependent transmission coefficients through the interfaces.
-In reference [20], the magnetoresistance of series of spin-valves with ultrathin Co layers inserted at the F/NM interface or moved back in the bulk of the F layers were quantitatively interpreted within this approach. This study underlined the importance of considering both the interfacial and bulk spin-dependent scattering to quantitatively interpret the GMR in spin-valves.
-Discussions on the validity and limitation of the semi-classical approach can also be found in references [13,14]. The overall conclusion of these studies is that a semi-classical approach which does not consider all details of the electronic band structure should be viewed more as a semi-quantitative than a quantitative result. However it can provide a quite useful guideline in the optimization of spin-valve structures.
Below are a few other examples of use of the code :

A) Influence of specular reflection on outer boundaries.

Several experimental papers have reported large enhancement in magnetoresistance amplitude by inserting the spin-valve sandwiches between insulating layers, especially NiO [13,21,22]. This effect has been qualitatively interpreted in terms of specular reflection of electrons at the metal/NiO interface. The mirror symmetry introduced by the specular reflection leads to the same enhancement in magnetoresistance amplitude as the increase of repeats in a GMR multilayer does. This effect can be quantified by using the present code. The figure below shows the variation of MR amplitude as a function of thickness of the pinned layer for various series of spin-valves of the form NiFe 70Å/Cu 22Å/Co t_{Co}/NiO in which we assume that the coefficient r of specular reflection of electrons at the Co/NiO interface can be changed (r=0 means complete diffuse scattering, r=1 means total specular reflection).

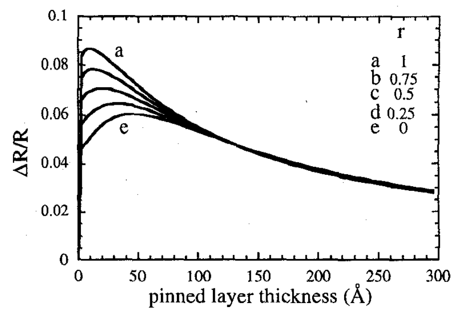

Figure 1: Magnetoresistance at 300K as a function of the thickness of the pinned layer (Co) in series of spin-valve structures of the form NiFe 70Å/Cu 22Å/Co t_{Co}/NiO for different values of the specular reflection coefficient at the Co/NiO interface. The microscopic parameters used are those listed in reference [19].

Two important results must be underlined in Figure 1, as the degree of specular reflection at the Co/antiferromagnet interface increases: i) the significant increase in the GMR amplitude for thin pinned layer, ii) the shift in the optimal thickness of the pinned layer. This result could be used in a predictive way in the optimization of the pinned layer thickness in such spin-valve structures [13].

B) Thermal variation of magnetoresistance :

The thermal variation of the spin-valve MR amplitude has been investigated in several series of FeMn and NiO based spin-valve structures by different groups [23,24]. In order to make these measurements more efficiently, a MRW tester has been developed at Phase Metrics which measures the transfer curves of thin film samples from room temperature (RT) to 200°C. Four-point probes are used to apply a constant DC current and accurately measure the generated voltage. An alternating magnetic field up to 500Oe is applied at a frequency between 0.1 and 50Hz. This setup has been used to characterize the thermal variation of several series of NiO based spin-valve samples prepared at CEA/Grenoble [25].

As an example, Figure 2 shows a compilation of results obtained on Co/Cu/Co spin-valves prepared in different groups. There are two striking features in the thermal variation of GMR in spin-valves: i) The decrease of MR is almost linear with temperature, ii) For a given couple of magnetic elements which form the free and pinned layers, the extrapolations of these linear behaviors to ΔR/R=0 converge towards a single temperature T_{0SV}.

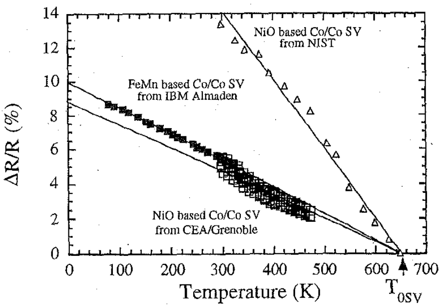

Figure 2 : Thermal variation of the magnetoresistance of several Co/Cu/Co spin-valve samples exchange biased by FeMn or NiO and prepared in three different groups. Black squares are data from [23], triangles are from [24], open squares are from this study (3 rampings up and down of the temperature between RT and 200°C). The lines are linear fits of the data.

The compilation of Figure 2 gives strong confirmation of the relevance of the characteristic temperature T_{0SV} already reported in [23]. Furthermore, the measurement carried out at Phase Metrics on NiFe/Cu/Co/NiO and Co/Cu/Co/NiO spin-valves confirms the point also underlined in [23] that T_{0SV} correlates with the Curie temperature of the ferromagnetic elements thus pointing out the major role of magnon scattering in the thermal decrease of the MR.

The present code can also be used to investigate the thermal variation of MR in spin-valve structures. As an example, Figure 3 shows calculated thermal variation of MR in series of spin-valves of the composition Co t_{Co}/Cu 22Å/Co 50Å/FeMn 100Å for various thicknesses of the sensing layer. In these calculations, the thermal variation of spin-conserving and spin-mixing resistivities of the various elements are taken from the literature [18]. The calculations have not been extended above 340K because no data on spin-mixing resistivities in these materials are available in the literaure above this temperature.

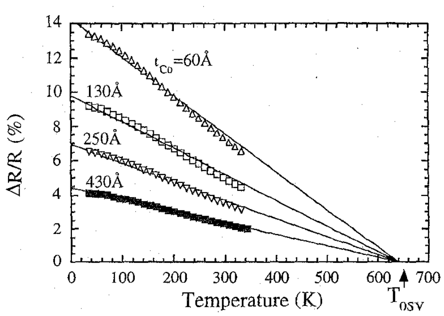

Figure 3: Calculated thermal variation of MR in a series of spin-valves of the composition Co t_{Co}/Cu 22Å/Co 50Å/FeMn 100Å. The points are the caluclated values, the lines are the linear extrapolations to Tosv.

The code reproduces the convergence of the MR(T) extrapolations towards a single characteristic temperature T_{0SV}. The calculated (Figure.3) and experimental (Figure.2) values of T_{0SV} are in good agreement.

IV. Conclusion

We have developed a code which calculates the conductance and magnetoresistance of spin-valve samples from the microscopic transport parameters. This code has been used in a quantitative or at least a semi-quantitative way. Through several examples, we have shown that it reproduces the main features of the variation of MR as a function of the thicknesses of the layers or temperature. This code can be used as a guideline in the optimization of the MR properties of spin-valves.

In addition, we confirm that in spin-valves of the form F1/NM/F2/AF, where F1 and F2 are ferromagnetic layers, NM a non-magnetic spacer, AF an antiferromagnetic layer, the thermal variation of MR extrapolates to $\Delta R/R=0$ at a temperature T_{0SV} which depends only on the couple (F1,F2) and correlates with the Curie temperature of these elements.

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