EFFECTS OF MAGNETIC AND NON MAGNETIC LAYER THICKNESS ON GIANT MAGNETORESISTANCE IN (NiFeCo/Cu) MULTILAYERS

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This paper presents a study of the magnetoresistance (MR) in the layered magnetic structure (NiFeCo/Cu). The effect of the magnetic (m) and non magnetic (nm) layer thickness (t_m , t_{nm}) and the composition of the magnetic layer has been discussed in the framework of the Johnson-Camley semiclassical approach, which is based on the Boltzmann transport equation. Our results are compared with the experiments and seem to show good agreement. Indeed, three main features of the MR are reproduced: (i) Presence of MR peak at t_m^{max} which vary with the magnetic layer composition, (ii) A MR decrease with non magnetic layer thickness t_{nm}, (iii) The increasing magnitude of MR ratio with increasing Co content.

I. INTRODUCTION

Giant magnetoresistance (GMR) has been observed for the first time in the Fe/Cr ferromagnetic multilayers [1]. Many systems have been tested and have shown GMR effects whose origin is attributed to oscillations of exchange coupling, alternately ferromagnetic (F) and antiferromagnetic (AF), giving rise to oscillations of the GMR with similar period. A maximum of GMR corresponds to AF coupling, and a minimum to F one. In this report, we describe the concentration and thickness dependence of the GMR at the first peak (maximum) in the (NiFeCo/Cu) multilayers.

II. EXPERIMENT

(NiFeCo/Cu) multilayers were prepared using rf diode sputtering at a base pressure (4.10^{-7} mbar). Corning 7059 glass was used as the substrates and a permanent magnet field (~300Oe) was held behind the glass to induce uniaxial anisotropy. But our measurements show that there is no trace of anisotropy in studied samples. The NiFeCo layers were obtained from Co disk target covered by NiFe chips. Multilayer and crystal structure were studied using low angle X-ray diffraction which indicates good multilayer structure. Sputtering rates were estimated from thickness measurements made with Tencor-1 profilometre of reference thick films. The chemical composition of the NiFeCo layer was obtained from Electron Probe Microanalyser. MR measurements were made using a linear four-point probe method with the current flowing in the film plane and along the induced easy-axis direction. The multilayers were prepared with 12 periods.

III. RESULTS AND DISCUSSION

We have made samples with several different NiFeCo alloy compositions layered with Cu spacers (Table 1). The thicknesses of NiFeCo layers were determined from sputtering rates and confirmed by magnetisation measurements.

	Ni%	Fe%	Co%	t_m(Å)
A	44	10	45	21.2
B	48	10.9	41	24
C	57.5	13	29	25.2
D	69	15.5	23	10

Table 1: Composition and thickness of magnetic layer.

GMR properties were first investigated as a function of Cu spacer thickness in the four series of $(NiFeCo(t_m)/Cu(t_{nm}))_{12}$ multilayers in which t_{nm} was varied from 7 to 31Å, with the magnetic layer thickness fixed at t_m for each series. This is presented on the figure 1 showing that the GMR oscillates with an average period of 12Å. This implies that the GMR found in our multilayers originates in the oscillating interlayer exchange coupling between the magnetic layers across the Cu layer. The first maxima corresponds to samples with weak thickness of Cu ($t_{nm}^{1\,max}$ =9.7; 10.3; 10.5; 11.3Å for multilayers A, B, C, and D respectively). When the fraction of Co in the magnetic layer is important, the first peak position is smaller approaching this of (Co/Cu) multilayers where $t_{nm}^{1\,max}$ = 9Å. The exchange coupling between adjacent magnetic layer is indeed AF. For all multilayers, the GMR ratio takes the second maxima at about the same thickness. Such oscillations were also observed in other systems such as: (Fe/Cr) [1] and (Co/Cu) [2].

In order to study more specifically the effect of magnetic and non magnetic layer thickness and the concentration of Fe, Co and Ni on the GMR, we have used the Johnson-Camley semiclassical model [3] which assume that the electron transport through the multilayer is governed by the Boltzmann equation, and that the

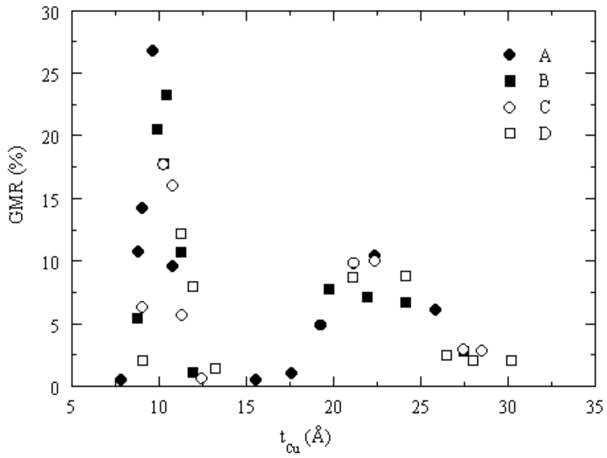

FIG. 1: Measured magnetoresistance versus thickness of the non-magnetic spacer layer for (NiFeCo/Cu) multilayers with different composition of magnetic layer.

electron distribution function f may be thought of as the Fermi- Dirac distribution $f_0^{\uparrow(\downarrow)}(v)$ plus corrections $g^{\uparrow(\downarrow)}(z,v)$ due to interfaces and the electric field:

$$f^{\uparrow(\downarrow)}(z,v) = f_0^{\uparrow(\downarrow)}(v) + g^{\uparrow(\downarrow)}(z,v) \quad (1)$$

where the arrows refer to the distributions for spin- up (spin- down) electrons.

Substituting Eq.1 into the Boltzmann equation written in a framework of the relaxation time hypothesis and considering only first order terms yields:

$$\frac{\partial g^{\uparrow(\downarrow)}}{\partial z} + \frac{g^{\uparrow(\downarrow)}}{\tau^{\uparrow(\downarrow)} v_z} = \frac{eE}{m v_z}\frac{\partial f_0}{\partial v_x} \quad (2)$$

where e and m denote the electron charge and electron effective mass, E is the applied electric field, and τ is the spin- dependent relaxation time. g may be separated into two parts, g_+ for electrons with positive v_z and g_- for electrons with negative v_z.

The general solution of Eq.2 can be written in the form:

$$g_\pm^{\uparrow(\downarrow)} = \frac{eE\tau^{\uparrow(\downarrow)}}{m}\frac{\partial f_0}{\partial v_x}\left[1 + F_\pm^{\uparrow(\downarrow)} \exp\left|\frac{-z}{\tau^{\uparrow(\downarrow)} v_z}\right|\right] \quad (3)$$

where F is an arbitrary function of velocity v, which is determined by the boundary conditions.

Once the F's are known, and thus the g's, the current density in each region may be calculated by integrating the perturbations $g^{\uparrow(\downarrow)}(z,v)$:

$$J_x(z) = -2e\left|\frac{m}{h}\right|^3 \int v_x g^{\uparrow(\downarrow)}(z,v) d^3v \quad (4)$$

The current in the whole structure may be easily calculated by integrating the current density over z, and thus the effective resistivity for the entire structure may be found.

$$\frac{1}{\rho} = 2e^2\left|\frac{m}{h}\right|^3 \frac{\tau^{\uparrow(\downarrow)}}{m}\int v_x \frac{\partial f_0}{\partial v_x}\left[1 + F^{\uparrow(\downarrow)} \exp\left[\frac{-z}{\tau^{\uparrow(\downarrow)} v_z}\right]\right] dz d^3v \quad (5)$$

Finally the magnetoresistance is:

$$MR = \frac{\rho_{AP} - \rho_P}{\rho_P} = \frac{I_P - I_{AP}}{I_{AP}} \quad (6)$$

We have supposed that interfaces constitute mixed layers containing an " alloying phase" formed through an interdiffusion of m and nm layers. Consequently, the mean free path (m.f.p.) for electrons of spin $\uparrow(\downarrow)$ is smaller in these interfaces $(\lambda_i^{\uparrow(\downarrow)} < \lambda_m^{\uparrow(\downarrow)}; \lambda_{nm})$. Furthermore, to deduce the m.f.p. that we have introduced to derive the GMR from the previous model, we have used expressions of spin dependent interface and bulk resistivities $(\rho_{\sigma i}, \rho_{\sigma b})$ given by [4]:

$$\begin{aligned} \rho_{\sigma i} &= c(D_{\sigma i}(Fe).x_{Fe} + D_{\sigma i}(Co).x_{Co} + D_{\sigma i}(Ni).x_{Ni}) \\ \rho_{\downarrow b} &= (x_{Fe}.x_{Co} + x_{Co}.x_{Ni} + 4.x_{Ni}.x_{Fe})R_{\downarrow} \end{aligned} \quad (7)$$

where c and $R_\downarrow$ are constants, x is the fraction of Ni, Fe and Co in NiFeCo alloy. $D_{\sigma i}$ are the densities of states at Fermi level for Ni, Fe and Co impurities in Cu respectively, whose values are obtained from the previous calculation [5]:

$$\begin{aligned} &D_{\uparrow i}(Fe) = 4;\ D_{\uparrow i}(Co) = 4;\ D_{\uparrow i}(Ni) = 6 \\ &D_{\downarrow i}(Fe) = 59;\ D_{\downarrow i}(Co) = 67;\ D_{\downarrow i}(Ni) = 21 \end{aligned} \quad (8)$$

For each ferromagnetic composition, we have calculated the GMR ratio as a function of non magnetic layer thickness (figure 2).

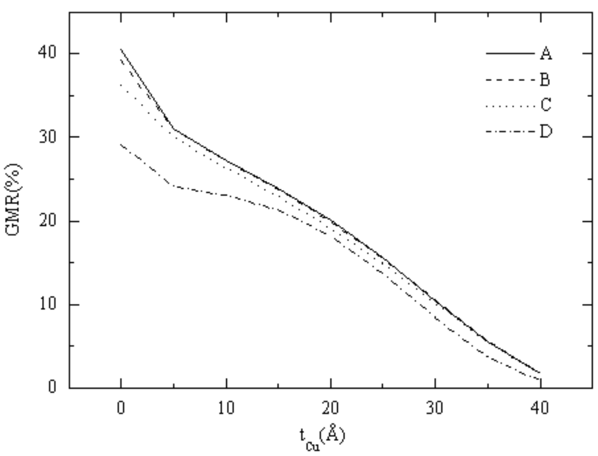

FIG. 2: GMR versus the thickness of the non magnetic spacer layer for A, B, C and D magnetic multilayers.

For all studied systems, the GMR decreases as t_{nm} increases. In fact, when the separating layer is thick, the conductivity through it becomes predominant and the spin dependent scattering effect is less effective, consequently

the GMR decreases. Similarly, the GMR decreases from system to an other less rich in Co. This could be explained by values of the density of states at Fermi level of electrons with spin down which are different for Co, Fe and Ni. Indeed, since this density for the Co is the greatest, the substitution of Co by Fe or Ni atoms leads to a diminution of the number of spin down porters and then, the passage from a Co rich system to an other with weak Co concentration provoke a GMR decrease.

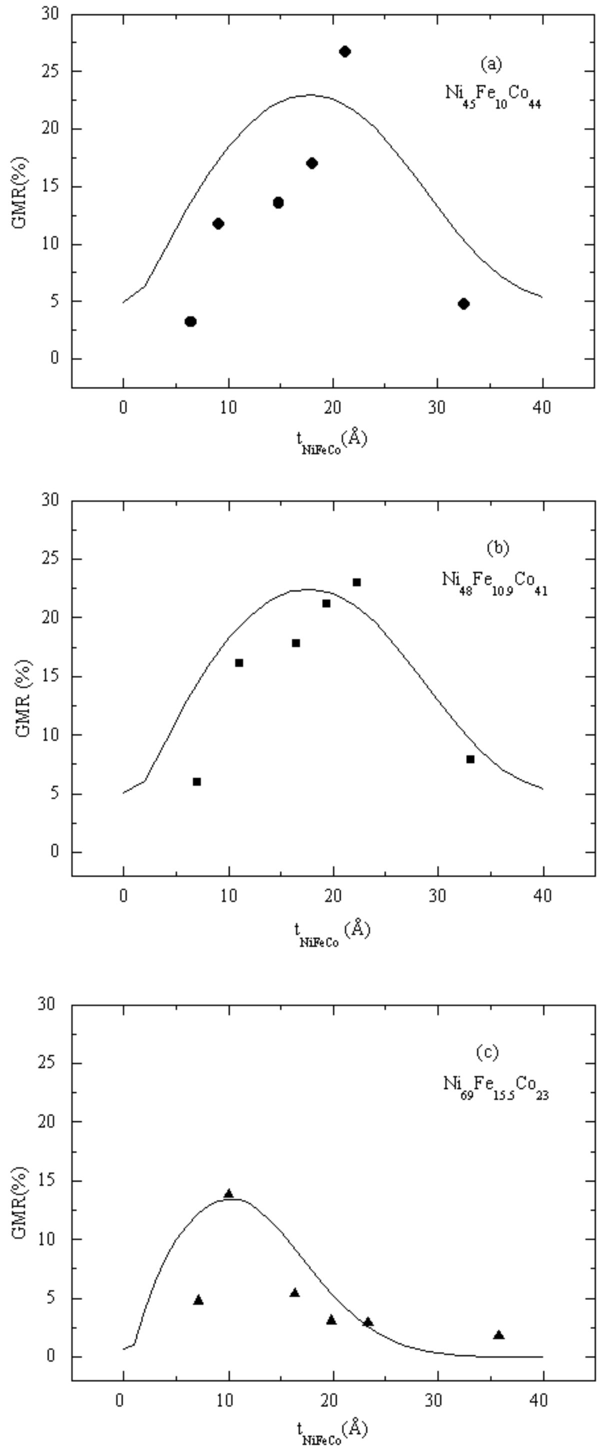

FIG. 3: Variation of the magnetoresistance ratio at the first peak ($t_{Cu} = t_{nm}^{1\,max}$) with the magnetic layer thickness for systems with Co concentrations of : 45% (a), 41% (b), and 23% (c). Solid lines are our calculations, and symbols are experimental measurements.

In figure 3 (a, b, c) we plot the evolution of the GMR with t_m for sample series A, B and D (the t_{nm} are fixed) on which, we have made experimental measurements. The qualitative reproduction of this evolution is enough satisfactory. The maximum of GMR as well as the corresponding magnetic layer thickness are all the more great that the fraction of the Co is important. So, GMR_{max}=23, 22.5, 13.5% for systems with 45, 41, 23% of Co in the magnetic layer respectively. This is coherent with the GMR evolution versus Co concentration previously shown on figure 2 and attributed to the difference between densities of states for Ni, Fe and Co.

For each of the three systems, the GMR increases with t_m to reach a maximum net enough at $t_m^{max} : (t_{m,A}^{max} = 19$ Å, $t_{m,B}^{max} = 18$ Å and $t_{m,D}^{max} = 10$ Å) which are comparable to measured values:
$(t_{m.A}^{max} = 21.2$ Å, $t_{m.B}^{max} = 22.3$ Å, and $t_{m.D}^{max} = 10$ Å) .
The GMR ratio decreases with increasing t_m at the thickness over t_m^{max} . Indeed, for large thickness t_{NiFeCo}, the magnetic layer can be divided into an active part contributing to the GMR and an inactive part farther from interfaces. This inactive part shunts the current and then decreases the magnetoresistance.

IV. CONCLUSION

We have used the Johnson-Camley semiclassical approach to reproduce the behaviour of the giant magnetoresistance in the (NiFeCo/Cu) magnetic multilayers. This study has allowed us to confirm the great sensitivity of the GMR to magnetic and non magnetic layer thickness, as well as to the composition of the magnetic layer.

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