Giant magnetoresistance in ($Ni_{80}Fe_{20}$/Cu) multilayers

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The dependence of the magnetoresistance (MR) ratio on the thicknesses of the magnetic (m) and non magnetic (nm) layers is studied for $Ni_{80}Fe_{20}$/Cu soft magnetic multilayers with a fixed number of bilayers (12). The highest value of the MR is 17,3% at Cu layer thickness of 7 Å. Very high sensitivity, around 132%/kOe has been observed. We present a discussion of the MR results using the Johnson-Camley semiclassical model based on the Boltzmann transport equation.

I. INTRODUCTION

Electrical transport properties of multilayers comprising ferromagnetic layers separated by non magnetic metallic (nm) layers have been studied experimentally by many groups [1-3]. Giant magnetoresistance (GMR) has been obtained in these structures in which the relative orientation of the magnetizations in successive ferromagnetic layers can be changed due either to the existence of an antiferromagnetic coupling through the spacer layer, or because of different coercitivities or exchange anisotropy. It is now widely admitted that the change of resistance results from a coherent interplay between the ferromagnetic layers of spin dependent scattering phenomena occurring at the interfaces and/or in the bulk of these layers. However, the saturation fields H_s of the multilayers are too high to be used for magnetoresistive sensors because the antiferromagnetic coupling between the magnetic layers is very strong. Much effort has been made to obtain new structure of multilayers which presents a high magnetoresistance ratio in low magnetic fields to be used for magnetoresistive heads.

In this study, we are interested to multilayers based on soft alloy NiFe which constitutes a well candidate to obtain a high sensitivity. We investigate the MR effects with different thicknesses of the NiFe and Cu layers using the Johnson – Camley semiclassical model [4].

II. EXPERIMENTAL PROCEDURE

NiFe/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. 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. 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

Samples measured are the NiFe/Cu multilayers for various nm layer thickness t_{Cu}=6.8 - 18Å.

A. GMR IN NiFe/Cu MULTILAYERS VERSUS Cu SPACER THICKNESS

Figure 1 shows the dependence of MR on Cu layer thickness for NiFe/Cu multilayers. The MR(t_{Cu}) presents an oscillatory behaviour that reflects the exchange coupling oscillations between ferromagnetic (F) and antiferromagnetic (AF) states.

The curve shows clearly the existence of two oscillations. The first one situates at t_{Cu}=7Å with MR ratio of 17.3% and the second one at t_{Cu}=15.5Å with MR ratio of 6.9%. The average distance between MR peaks gives a period of oscillations of 8.5Å which is inferior to that observed in Co/Cu (12Å) and NiFeCo/Cu (10Å) multilayers. These peaks correspond to AF coupling between successive magnetic layers.

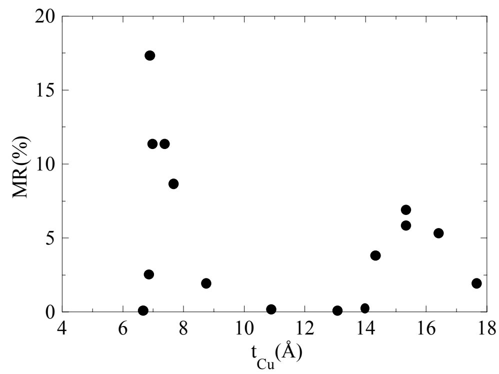

FIG. 1 : Measured magnetoresistance versus thickness of the non magnetic spacer layer for NiFe/Cu multilayers.

Figure 2 shows the ($Ni_{80}Fe_{20}$/Cu) multilayers X-ray diffraction spectra at the first and second magnetoresistance peaks (t_{Cu}=7Å and 15.5Å respectively). The multilayers are thought to show (111) preferred orientation.

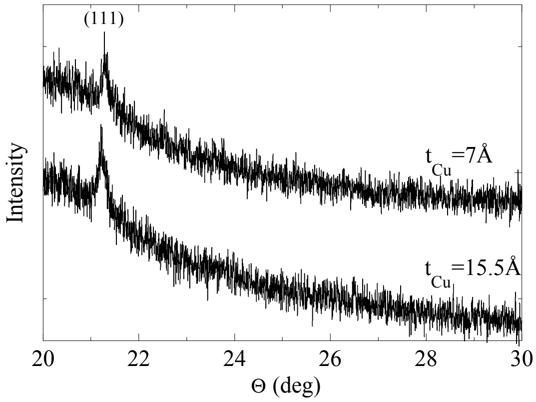

FIG. 2: X-ray diffraction spectra for ($Ni_{80}Fe_{20}$/Cu) multilayers.

Figure 3 shows the magnetoresistance effects in the NiFe/Cu multilayers with different Cu layer thicknesses. Their general appearance is typical enough of a classical behaviour of MR evolution with magnetic field as that has been observed in many multilayers based on a ferromagnetic transition metal and a non magnetic layers [5,6]. Thus at zero field, the exchange interaction through the non magnetic layer aligns antiparallel the magnetization of NiFe neighbour layers, what is traduced by high resistivity. The passage from (AF) state to (F) one by the application of magnetic field is accompanied by a decrease of the resistance. This is traduced on the figure by the MR peak at H=0kOe.

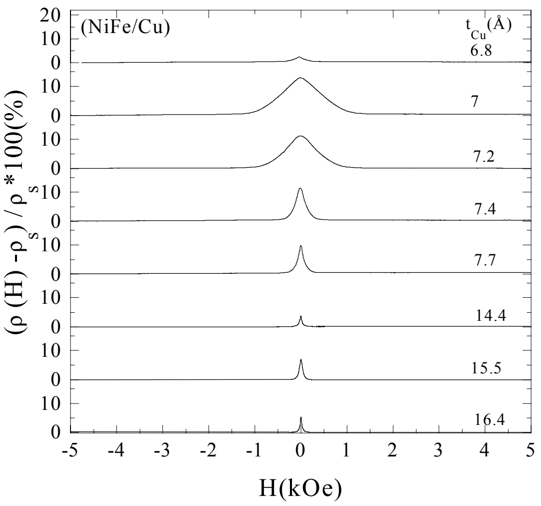

FIG. 3 : Magnetoresitance curves of the NiFe/Cu multilayers for different Cu layer thicknesses.

B. GMR SENSITIVITY

The NiFe is one of the soft magnetic materials introduced to increase the sensitivity S defined as: $S=\Delta MR/\Delta H$. High sensitivity means a relatively large percentage change in electrical resistance per unit applied magnetic field. Values of sensitivity obtained in our multilayers are presented on figure 4. This sensitivity is maximal near MR peaks. So, it's 79%/kOe at the first peak and 132%/kOe at the second peak. These maximums are greater than those obtained in (Co / Cu) and NiFeCo/Cu multilayers which are at the second peak 43%/kOe and 68%/kOe respectively.

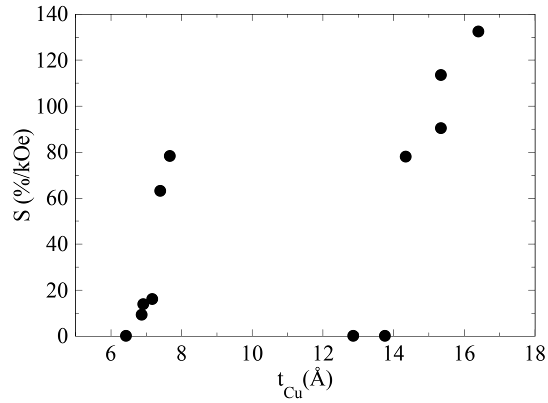

FIG. 4: Magnetoresistance sensitivity dependence of non magnetic spacer layer thickness for NiFe/Cu multilayers.

The greatest value of the sensitivity observed at the second peak can be resulting from a double effect acting on MR_{max} and H_s. So, $S_{max} = \frac{MR_{max}}{H_s}$, thus when t_{Cu} increases, the maximum of MR ratio decreases, on the other hand the AF coupling becomes weaker what induced a parallel alignment of neighbour NiFe layer magnetization and therefore the saturation field H_s decreases, suggesting that for the second peak, H_s decrease swiftly and thereby $(S_{max})_{first\ peak} < (S_{max})_{second\ peak}$.

C. GMR in NiFe/Cu MULTILAYERS VERSUS NiFe THICKNESS

Figure 5 describes the MR variation versus the magnetic layer thickness for NiFe/Cu multilayers with a fixed non magnetic spacer layer thickness. The MR ratio presents a maximum of 17.3% at t_{NiFe}=18.8Å. At the thickness over 18.8Å the MR decreases what could be explained by the appearance of the inactive region which shunts the current.

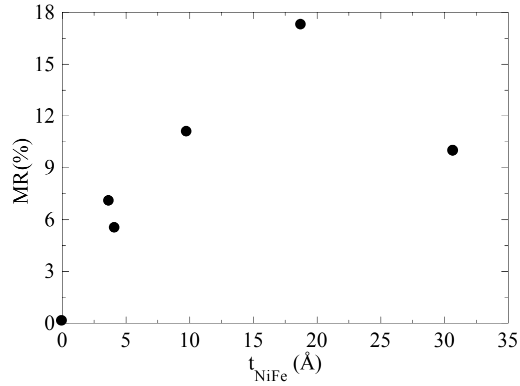

FIG. 5: MR ratio as a function of t_{NiFe} for NiFe/Cu multilayers.

Figure 6 shows magnetoresistance ratio for the NiFe/Cu multilayers versus the magnetic field at the first peak of oscillation (t_{Cu}=7Å) for magnetic layer thickness going from 3.7Å to 30.7Å. The shape of the curves does not change but the magnitude of both MR ratio and saturation field H_s vary. The MR ratio exhibits a maximum at t_{NiFe}=18.8Å. As the NiFe layer thickness increases above 18.8Å, the MR ratio begins to decrease, possibly this results from the shunting of the current in the NiFe layer. On the other hand, H_s decreases rapidly with increasing t_{NiFe}. In general, the antiparallel interlayer exchange coupling strength J can be calculated from $J=M_sH_st_{NiFe}/4$ where M_s is the saturation magnetization. As the thickness of the NiFe layer increases, the saturation magnetization of the NiFe layer increases. This is because the fraction of magnetic atoms neighbouring each other in each NiFe layer increases as the thickness of the NiFe layer increases. The decrease in the saturation field of the multilayers can be also explained in terms of the increase in the saturation magnetization of the NiFe layer. For the lower saturation magnetization, the torque to direct the magnetization to the applied field becomes smaller. The smaller torque causes the higher saturation field because the interlayer coupling constant J can be considered almost unvarying as observed previously [7].

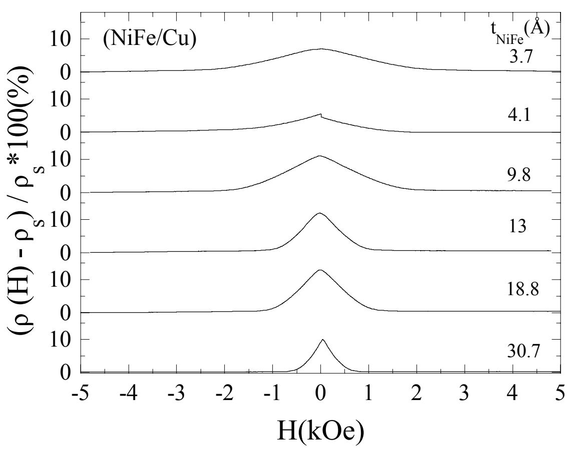

FIG.6: Magnetoresistance curves of NiFe/Cu multilayers for different magnetic layer thickness.

IV. DISCUSSION

In order to study more specifically the effect of magnetic and non magnetic layer thickness on the GMR, we have used the Johnson-Camley semiclassical model [4] which assume that the electron transport through the multilayer is governed by the Boltzmann equation and that the electron distribution function $f^{\uparrow(\downarrow)}(z,v)$ may be decomposed into two parts; the equilibrium (in zero electric field) distribution function $f_0(v)$ and corrections $g^{\uparrow(\downarrow)}(z,v)$ due to interfaces and the electric field:

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

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

The Boltzmann equation used is:

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

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 is separated into two parts ; g_+ for electrons with positive v_z and g_- for negative v_z .

The general solution of the Boltzmann equation can be written as:

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

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 is obtained by integrating $g^{\uparrow(\downarrow)}(z,v)$.

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. Finally the magnetoresistance is:

$$MR = \frac{\rho_{AP} - \rho_P}{\rho_P} = \frac{I_P - I_{AP}}{I_{AP}}$$

In the studied multilayers, we have taken as values of mean free path (M. F. P) in the NiFe and Cu layers:
$\lambda^{\uparrow}_{NiFe} = 114$Å, $\lambda^{\downarrow}_{NiFe} = 12$Å et $\lambda^{\uparrow}_{Cu} = \lambda^{\downarrow}_{Cu} = 205$Å [8]. Parameters of interfaces $\lambda^{\uparrow}_i, \lambda^{\downarrow}_i$ are left free to vary . The interfacial thickness t_i has to be fixed correctly after a characterisation of the interface roughness.

On the figure 7, we have represented the variation of the GMR calculated envelop versus the Cu layer thickness. The best agreement between this calculated MR envelop and experimental results is obtained for next interface parameters: t_i = 4.8 Å, $\lambda^{\uparrow}_i = 20$Å and $\lambda^{\downarrow}_i = 10$Å. This shows that the spin dependent scattering asymmetry coefficient $\alpha=\lambda^{\uparrow}/\lambda^{\downarrow}$ is greater in the volume of NiFe layers that in interfaces. Indeed α_{NiFe}= 9.5 and α_i=2.

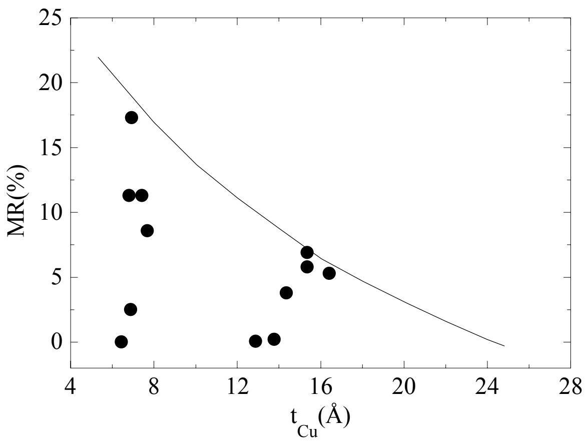

FIG.7 : Calculated magnetoresistance versus the thickness of the non magnetic spacer layer of NiFe/Cu multilayers (Solid line). Symbols represent experimental results.

The figure 8 illustrates the dependence of the MR on magnetic layer thickness. The MR ratio exhibit a broad peak at t_{max} ≅15-18Å thick NiFe and decreases with increasing t_{NiFe} at the thickness over t_{max}. Indeed, for large NiFe layer thickness, the inactive part appears and shunts the current.

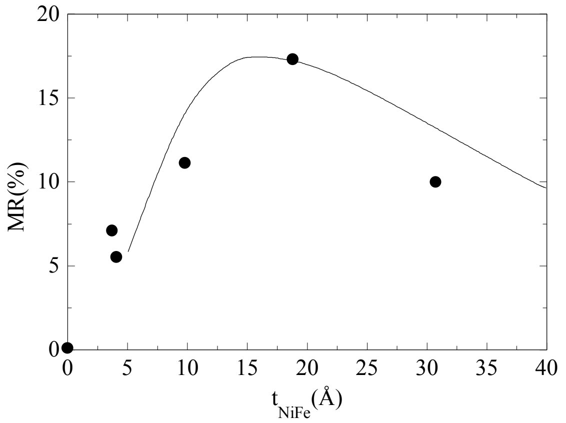

FIG. 8 : in magnetoresistance with changing thickness of Changes magnetic layer for NiFe/Cu multilayers. Solid line represents the calculated MR while symbols represent experimental results.

By taking into account the constitution of mixed zones containing an "alloying phase" formed through an interdiffusion of m and nm layers as we have suggested previously for NiFeCo/Cu [9] and CoZr/Cu/Co [10], the best fitting for the studied multilayers system is obtained for a minimal interfacial roughness corresponding to a weak alloy concentration C_{alloy}.

This confirms the above high values of α_{NiFe} and that the spin dependent scattering is mostly bulk with NiFe, which is in good agreement with the results obtained previously[8].

V. CONCLUSION

We investigated the magnetoresistance in the NiFe/Cu multilayers prepared by sputtering method. The following results were obtained:

(1) The MR ratio depends on the distance between magnetic layers. The maximum ratio was about 17.3% at t_{Cu}=7Å.

(2) The MR ratio exhibits a broad peak at a magnetic layer thickness of 18.8Å.

(3) Very high value of the sensitivity was obtained, and it is more greater at the Cu layer thickness corresponding to the second peak of the MR oscillation.

(4) The spin dependent scattering is mostly bulk in NiFe/Cu multilayers.

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