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The effect of the interface roughness on the magnetotransport properties in $Ni_{81}Fe_{19}$/Zr multi-layers

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ABSTRACT

In this work, we study the effect of the chemical and/or structural disorder existing in the interface on the magnetotransport properties of the multilayered system NiFe/Zr. The assumption that the possible apparition of a disordered alloying phase NiFeZr is caused by diffusion of non-magnetic alloying Zr atoms at the interface is proposed. This assumed interfacial degradation is used to calculate the magnetoresistance rate $MR_{cal}(t)$ in the framework of Johnson–Camley semi-classical model. This allowed us to reproduce quite faithfully the experimental measured results $MR_{exp}(t)$, confirming thus the important role of the interface roughness on the electronic transport properties. The behavior of calculated and measured magnetoresistance versus NiFe magnetic layer thickness ($t=t_{NiFe}$) shows one maximum of 1.8% at $t_{NiFe}=80$ Å. When the thickness of the non-magnetic layer t_{Zr} varies, the $MR(t_{Zr})$ ratio shows an oscillatory behavior with an average period (7 Å). An overall weakness is showed by measured rate probably due to a degradation of the interface quality.

1. Introduction

Even more than a decade after the discovery of the GMR effect in Fe/Cr thin film multilayers [1–3], magnetic multilayers systems composed of alternating of magnetic and non-magnetic layers still attract considerable amount of scientific interest because of their already proved utility in data storage and magnetic sensor technique. One of the main aims of these studies is to improve the magnetic sensitivity ($S=\Delta R/R\Delta H$). Thus a special attention was given to multilayers based on NiFe layers because of the soft magnetic character that they exhibit.Theoretical investigation showed that the GMR effect is closely related to the spin dependent scattering asymmetry effect of the conduction electrons both in bulk and interface which is a characteristic property of the transition metal (TM) elements like Fe and Ni. When an electron crosses one of the magnetic layers it is easily transmitted if its spin is parallel to the magnetization vector of the magnetic layer leading to weak MR ratio, whereas this electron is diffused in the contrary magnetic configuration supporting MR. Moreover the composition and the quality of the interface have an important role on the electronic transport proprieties [4]. In fact the values of the mean free path (MFP) and the spin dependent scattering asymmetry coefficient (SDSA) depend strongly on the interface roughness [5].

In this work, we present a study of the interface quality effect on the magnetotransport properties of $Ni_{81}Fe_{19}$/Zr magnetic multilayer using the semi-classical model of Jhonson–Camely [6] based on the resolution of the Boltzmann transport equation and adapted to the interface degradation approach. A good agreement between experiment and calculation results is obtained.

2. Experimental methods

The multi-layer $Ni_{81}Fe_{19}$/Zr studied were prepared by the method of cathode sputtering with a magnetron by using NiFe and Zr targets of high purity. The pressure of the room before the deposit was about 6×10^{-8} Torr, while the pressure of the gas (ultra-high purity Ar) was maintained constant at 2×10^{-3} Torr. The DC power was 80 W. The films were deposited on a water-cooled Si(001) substrate maintained at a temperature of 293 K. The multi-layers were prepared in two series of samples S_1 and S_2 follows as: (i) S_1: Magnetic layer thickness t_{NiFe} varying in $20\text{ Å}\le t_{NiFe}\le 120\text{ Å}$ when the non-magnetic layer thickness was fixed at $t_{Zr}=15$ Å; (ii) S_2: non-magnetic layer thickness t_{Zr} varying within $3\text{ Å}\le t_{Zr}\le 20\text{ Å}$ for a fixed magnetic layer thickness at $t_{NiFe}=30$ Å. The choice of $t_{NiFe}=30$ Å is imposed by the fact of being able to measure the impact of variation of the thickness of the non-magnetic Zr layer on the magnetotransport properties in NiFe/Zr. Indeed, according to high-angle X-ray (HXRD) diffraction measurements performed previously on this multilayered system [7], when the magnetic layers are thick ($t_{NiFe}\ge 60$ Å) the effect of

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the non-magnetic Zr layer is practically masked, while for very low magnetic thicknesses ($t_{NiFe} \le 20$ Å) the effect of these magnetic layers is not probed (disappearance of the Bragg peak (111) NiFe at $t_{NiFe} = 20$ Å).

3. Results

3.1. Measured magnetoresistance rate MR_{exp}

The dependence of the measured $MR_{exp}(t)$ ratio on magnetic and non-magnetic layer thickness in $Ni_{81}Fe_{19}$/Zr multilayer at room temperature is shown in Figs. 1 and 2 (Symbols). Fig. 1 depicts the evolution of $MR_{exp}(t = t_{NiFe})$ for the series S_1. The main features of this evolution show that for $t_{NiFe} > 40$ Å the MR increases with increasing t_{NiFe} and exhibits a maximum of about 1.8% at $t_{NiFe}^{max} = 80$ Å. The MR ratio then gradually decreases with increasing t_{NiFe} until it reaches a minimum of about 0.5% at $t_{NiFe} = 120$ Å. For $t_{NiFe} < 40$ Å, a very weak MR ratio is obtained, showing that the magnetotransport process is strongly blocked at the interface, and generally the maximum ratio MR^{max} obtained in the present structure is much smaller compared to other ratios obtained in similar systems such as NiFe/Cu [8,9].

Fig. 2 shows the curve $MR_{exp}(t_{Zr})$ for the series S_2. $MR_{exp}(t_{Zr})$ presents an oscillatory behavior reflecting the oscillations of the exchange coupling between ferromagnetic (F) and antiferromagnetic (AF) configurations of the magnetization vectors of the adjacent magnetic layers NiFe. It shows clearly the existence of two oscillations. The first one at $t_{Zr} = 7$ Å with ratio of 0.4% and the second one at $t_{Zr} = 14$ Å with ratio of 0.3%. These values of MR peaks are relatively weak because they are obtained for fine magnetic layers ($t_{NiFe} \le 40$ Å) where a disorder caused by the diffusion of non-magnetic alloying metal Zr in the interface provokes an important degradation of crystallinity of this interface where the existence of an amorphous phase was shown experimentally [7]. The average distance between MR peaks gives a period of oscillations of 7 Å which is inferior to these observed in other multilayer based on similar transition metal alloys deposited on copper such as NiFe/Cu (8.5 Å) and NiFeCo/Cu (8.5 Å) [9].

3.2. Calculated magnetoresistence ratio MR_{cal}

The calculation of magnetoresistence ratio MR_{cal} is carried out within the framework of the semi-classical Johnson–Camley (J–C) model based on the Boltzmann transport equation. The J–C model

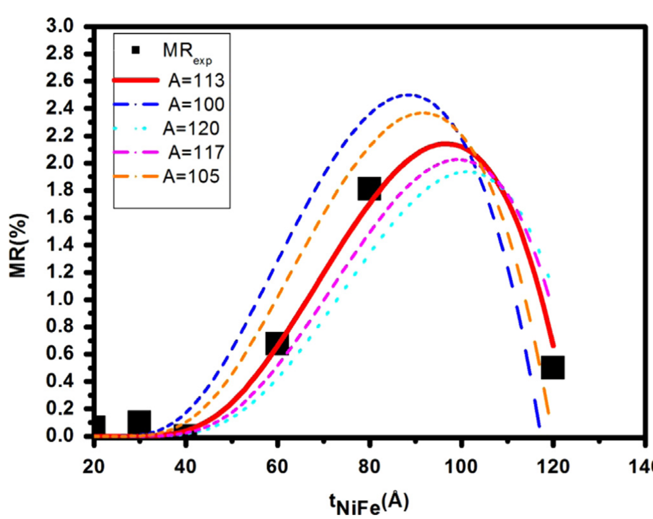

Fig. 1. Comparison of $MR_{cal}(t_{NiFe})$ (continuous curve) with $MR_{exp}(t_{NiFe})$ (symbols).

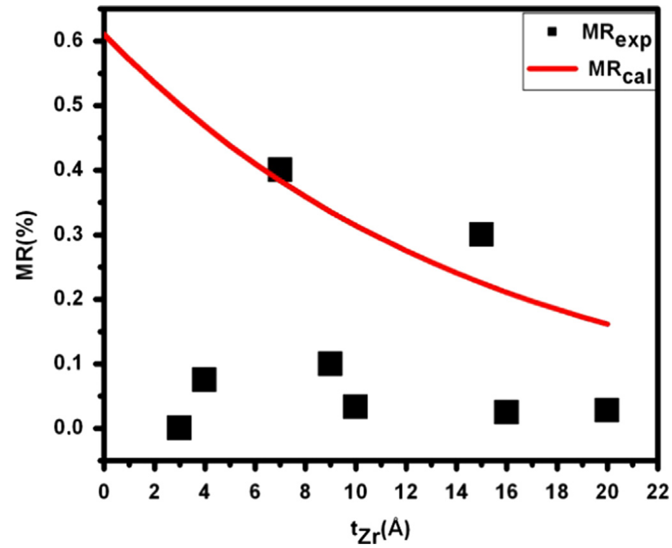

Fig. 2. Variation of $MR_{cal}(t_{Zr})$ (continuous curve) and $MR_{exp}(t_{Zr})$ (Symbols).

takes account primarily of the interaction mixing the s–d states contribution to the exchange coupling between two successive magnetic layers NiFe and based on the assumption of spin-dependent scattering asymmetry of the conduction electrons. The other contribution to the exchange described by RKKY approximation is known to be coarse enough in the case of 3d-TM and alloys like NiFe studied here [10]. In the multi-layer containing TM or their alloys such as NiFe/Zr the GMR effect is attributed to the mechanisms of scattering depending on spin. The electronic conduction is supposed to be carried out in two channels of electrons with independent opposite spins ($\sigma = \uparrow, \downarrow$). Indeed, the existence of a fairly strong local magnetic field in these TM is a sign of a strong separation of spin exchange. The Fermi surfaces with majority and minority spins can have very different topological forms leading to notable differences in densities of states corresponding to the Fermi level [11]. Consequently the electronic probabilities of s–d transitions are different for the two directions of spin leading to two distinct currents. Then we assumed that the electron transport through the multilayer is governed by the Boltzmann equation for the electron distribution function $f(\vec{r}, \vec{v})$ given in the relaxation time τ approximation by $\vec{v}.\vec{\nabla}_{\vec{r}} f(\vec{r}, \vec{v})(-e/m)\vec{E}\,\vec{\nabla}_{\vec{v}} f(\vec{r}, \vec{v}) = (-(f(\vec{r}, \vec{v}) - f_0(\vec{v}))/\tau)$.

Here $(\vec{r}, \vec{v})$ is the canonical pair of position and velocity of an electron and f_o is the Fermi–Dirac distribution. Then we can write, for each spin $\sigma : f^\sigma(\vec{r}, \vec{v}) = f_0^\sigma(\vec{v}) + g^\sigma(\vec{r}, \vec{v})$, where $g^\sigma(\vec{r}, \vec{v})$ defines the difference between the ground state population $f_0^\sigma(\vec{v})$ and the perturbed state population $f^\sigma(\vec{r}, \vec{v})$ owing to the interfaces and the electric field. It corresponds to only electrons involved in transport phenomena. For a static and uniform electric field $\vec{E}$ applied along the direction $\vec{x}$ of a multilayered system stacked along the direction $\vec{z}$, the translational invariance in the plane of the layers (*x*,*y*) implies that the final solution depends only the direction $\vec{z}$ and the Boltzmann equation becomes

$$\frac{\partial}{\partial z} g_{\pm}^{\sigma}(\vec{r}, \vec{v}) + \frac{1}{\tau^\sigma v_z} g_{\pm}^{\sigma}(\vec{r}, \vec{v}) = \frac{eE}{m v_z} \frac{\partial}{\partial v_x} f^0(\vec{v}) \tag{1}$$

leading to the solution

$$g_{\pm}^{\sigma}(z, v_z) = \frac{eE\tau^\sigma}{m} \frac{\partial f_0}{\partial v_x} \left[1 + F_{\pm}^{\sigma} \exp\left[\frac{-z}{\tau^\sigma v_z} \right] \right] \tag{2}$$

where *F* is an arbitrary function of velocity *v*, determined by the boundary conditions, *e* and *m* denote respectively the electron