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Exchange coupling and giant magnetoresistance in magnetic multilayered structures

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Our paper presents different magnetic multilayered systems, that were fabricated in order to allow the study of the giant magnetoresistance (GMR) effect and of the magnetic coupling of two ferromagnetic layers separated by a non-magnetic one. study the GMR response alone, we have developed a structure based on the Co/Cu/Fe tri-layer system. Due to the difference in coercive fields, H_c, of Co and Fe, we were able to stabilize both a parallel and an anti-parallel configuration of the magnetizations of the two layers, thus being able to observe the GMR response of the structure. As far as the study of the exchange coupling of ferromagnetic films is concerned, we used the Co/Ru/Co systems, with varying thicknesses of the Ru layer. An optimum of 8Å for the Ru layer was obtained for the antiferromagnetic coupling of the Co layers. Also, a hybrid Co/Ru/Co/Cu/Fe structure was fabricated, in which we show the way the coupled layers modulate the GMR response of the entire structure.

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1. Introduction

Since the discovery of giant magnetoresistance (GMR) effect in antiferromagnetically coupled magnetic multi-layers [1, 2], materials showing GMR have attracted interest due to their importance both for a fundamental understanding of the spin-dependent electron transport mechanism and for device applications. The GMR effect occurs when changing the relative orientation of the magnetization of two ferromagnetic layers, separated by a non magnetic one, from parallel to anti-parallel and it consists of a dramatic change in the sample's electrical resistance when passing from one magnetic configuration to the other. The reversal of the magnetization of the two ferromagnetic layers can be achieved by choosing an appropriate multilayer configuration, when applying a magnetic field. The first system that we developed consisted of a Co/Cu/Fe multilayered structure. The reversal of the relative orientation of the ferromagnetic layers magnetization can be achieved by applying an external magnetic field and choosing an appropriate multilayer configuration. Because of the difference in coercive fields, H_c, of the Co and Fe layers, their magnetizations switch independently, allowing us to stabilize both parallel and anti-parallel alignment of their respective magnetizations, and thus to observe the GMR response of the system. Another approach used to develop structures that exhibit GMR, was to pin the magnetization of one of the layers and allowing the magnetization of the remaining layer to switch freely in the direction of the external applied magnetic field. For this purpose we synthesized a Co/Ru/Co sequence in which the Co layers are antiferromagnetically coupled by means of indirect exchange interaction [3]. This coupling acts as pinning for the Co layer. On top of this structure we then deposited the Cu/Fe layers, with the Fe layer as the free layer.

2. Experimental

The growth of all presented samples was done *in-situ* in a high vacuum electron beam deposition chamber having a pressure of about 10^{-7} Torr. The layers were grown on Si(111) substrates. In order to obtain good morphological quality of the layers and the interfaces a 30nm thick Ru buffer layer was deposited. To ascertain the flatness of the buffer layer, the substrate was heated during and 30 minutes after the deposition, up to 400 °C. On top of all of the structures a Cr layer of 2nm was deposited as a cap layer, to serve as protection against oxidation of the rest of the structure. The topography of the surface of the buffer was studied using an *ex-situ* atomic-force microscopy (AFM). The electrical resistance of the samples was measured using the four-point technique, having the current passing in the plane of the sample (CIP geometry). The external applied field was produced with a water cooled electromagnet, and it could be raised to values as high as 10^4 Oe. The magnetic properties of our structures were measured using a vibrating sample magnetometer (VSM).Give a description of the experimental methods used.

3. Results

We shall divide this section into three different paragraphs, each presenting the experimental data obtained on the different elaborated structures.

3.1. The Co/Cu/Fe structure

The sample has the following composition: Si/Ru(30nm)/Co(6nm)/Cu(6nm)/ Fe(10nm)/Cr(2nm). In situation denoted by (1) the applied magnetic field saturates the magnetizations of the Fe and Co layers, leading to a parallel alignment of the two. This parallel configuration results in a low resistance state. When the orientation of the magnetic field is reversed and further increased, (2), the magnetization of the iron layer is reversed. This reversal leads to a non-parallel orientation of the magnetizations of the layers corresponding to a high resistance of the sample.

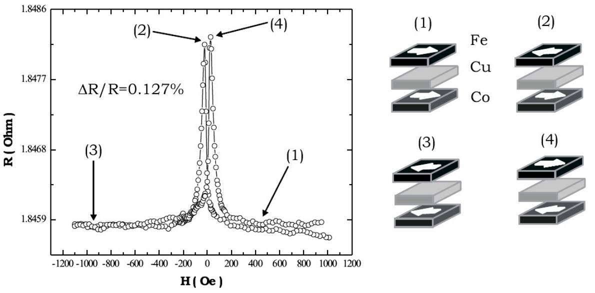

Fig. 1. The dependence of the resistance of the Co/Cu/Fe structure as a function of the applied magnetic field and the configuration of the magnetizations of the magnetic layers at different values of the magnetic field.

By further increasing the field the magnetizations will be saturated in the field's direction leading consequently to a low electrical resistance of the sample, (3). By decreasing the field's magnitude and reversing its orientation, we find a symmetric behavior of the system, (4). The value of the magnetoresistive factor, defined as:

$$\frac{\Delta R}{R} = \frac{R_{antiparallel} - R_{parallel}}{R_{parallel}}, \qquad (1)$$

has a value of 0.127%. Prior to the deposition of this structure, individual layers of both Fe and Co were deposited and magnetically characterized. We concluded from those studies that the coercive field of the Co films is higher than that of the Fe ones, allowing us to give the above explanation of the R(H) curve. However, the GMR ratio, (1), is quite small. This cannot be due to the poor quality of the films, as the AFM studies we have performed on the different layers of the structure reveal a RMS roughness around 0.2 nm. Instead, the diffusion of the Co layer into the Ru buffer is not negligible [4]. Magnetic measurements and calculations reveal the fact that there is a magnetic dead layer due to diffusion. For example for 7nm, 8nm and 9nm grown Co layers the "active" parts are only of 4.75nm, 6.45nm and 7.64nm. This averages to a 1.7nm of Co diffused in the buffer layer which favors the spin scattering, reducing the spin polarization and thus the magneto-resistive ratio.

3.2. The Co/Ru/Co structure

For the study of interlayer exchange coupling between two magnetic layers separated by a non-magnetic metallic film we have developed the Co/Ru/Co structure, for which we varied the thickness of the Ru layer form 0.6 nm to 1.5nm.

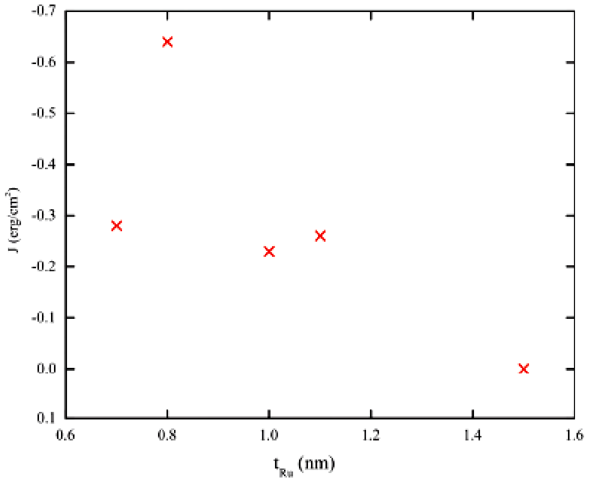

Fig. 2. The variation of the interlayer exchange coupling strength with the thickness of the Ru spacer layer. A maximum of -0.64 erg/cm^2 was obtained for a Ru thickness of 0.8 nm.

The bilinear exchange coupling constant for a *double* layer with magnetic films of equal thickness t and magnetization M has the form [9]: $J = -\mu_0 M H_S t / 2$, where H_S is the field where the M(H) curve saturates. In order to assure a good coupling, that is to obtain a high absolute value of the coupling constant J, one must be able to grow high quality films. AFM studies of the Ru buffer layer, the first Co layer and of spacer Ru layer were performed.

These revealed good morphological properties of the film, with a RMS roughness varying from 0.16 nm to 0.25 nm. In Fig. 2 the coupling constant is plotted as a function of the thickness of the Ru layer. It can be seen that a maximum was obtained for 0.8nm of Ru, and also that J is negative, indicating antiferromagnetic coupling of the Co layers. In Fig. 3, we present the magnetization curve measured on the structure having a 0.8nm Ru spacer layer.

The coupling is destroyed at around 2000 Oe, after which a continuous rotation of the magnetizations is observed.

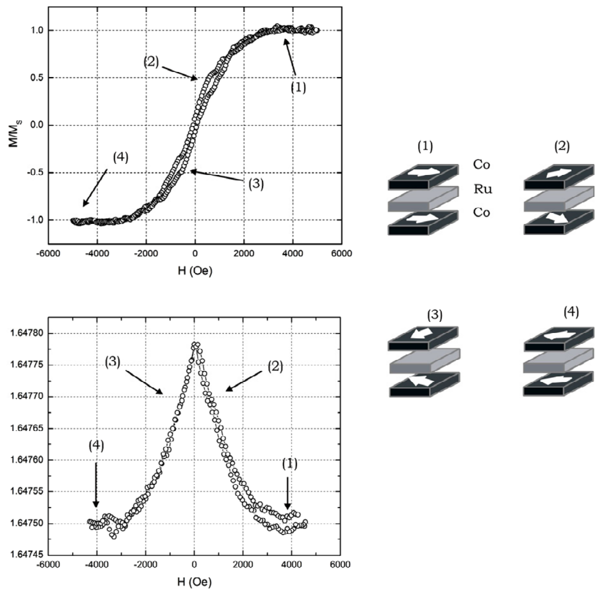

Fig. 3. Magnetization of the structure with t_{Ru}=0.8 nm. A continuous rotation from parallel to antiparallel state is observed, and magnetoresistance measurement of the sample. (t_{Ru}=0.8).

Correspondingly, the magnetoresistance increases as the coupling tends to align the magnetizations of the Co films in an anti-parallel configuration. The linear dependence of the structure's resistance as a function of the applied magnetic field in the (0, ±1500 Oe) interval, suggests possible sensor applications. The Co/Ru/Co interlayer exchanged coupled system can be used as a "hard magnetic layer" in the spin valve system. If the thicknesses of the two ferromagnetic layers are different, the system will have an amplified coercive field, relative to the uncoupled system, due to a reduced effective magnetic moment [5]. Studies concerning this property will be published elsewhere [6].

3.3. The Co/Ru/Co/Cu/Fe structure

As stated before, instead of a simple Co layer, for the layer with hard magnetization, we used an artificial antiferromagnetic (AAF) [5,7,8] structure to pin the Co layer. The two magnetic layers are coupled with their magnetizations in an anti-parallel configuration, through the Ru layer, by means of indirect exchange coupling. The structure of the sample is: Si/Ru(30nm)/Co(3nm)/Ru(0.8nm)/Co(3nm)/Cu(6nm)/Fe(10nm)/Cr(2nm). The resistance measurement as a function of the applied field is given in Fig. 4. As it can be seen, here the form of the GMR signal is quite different from the other samples.

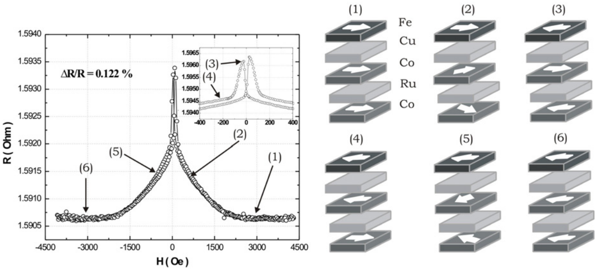

Fig. 4. The dependence of the resistance of the Co/Ru/Co/Cu/Fe structure as a function of the applied magnetic field and the configuration of the magnetizations of the magnetic layers at different values of the magnetic field.

First, the saturation field, the field at which all the magnetizations are parallel, is much higher, about 2000 Oe, with respect to 200 Oe, in the case of the other samples. This is explained by the fact that the coupling is strong and in order to break it, a large external field is required. After the value of the field is reduced, the magnetizations of the two Co layers are no longer parallel but not yet anti-parallel, they make an angle θ, between them, and so the resistance starts to increase (2). The resistance of the sample further increases as the exchange interaction tends to align the magnetizations anti-parallel. At low fields the AAF configuration is reached. When the field is reversed and increased the magnetization of the Fe layer is switched and there is a sharp peak (3). Further increasing the field the AAF is switched by 180^{o} (4). When the field is sufficiently high it starts to break the coupling between the layers (5). This situation is marked by a decrease in resistance as the layers tend to be orientated parallel. Saturation is reached at (6), and the resistance stays afterward at a constant value. On return the situation is almost symmetric. The magnetoresistive ratio is 0.122%.

5. Conclusions

The samples were elaborated by means of UHV e-beam evaporation technique. The AFM measurements showed good interfacial quality of the films, RMS less than 0.3nm. A maximum in interlayer exchange coupling strength in the AAF structure was obtained for a Ru thickness of 0.8 nm. For thicknesses larger than 1.4 nm the interlayer exchange coupling vanishes. The variation of the magnetoresistance of the AAF system exhibits a linear regime in the (0,±1500 Oe) interval, interesting for potential sensor applications. Also, the Co/Ru/Co structure can be used as a coercive field amplifier if the thicknesses of the two magnetic layers are not equal. For the Co/Cu/Fe spin valve system a magnetoresistive ratio of 0.127% was obtained, while in the case of the spin valve using the AAF, this ratio was of 0.122%.

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