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4f–3d exchange coupling in Gd/X/Co (X = Pt, Cr) multilayers

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Abstract

We have studied the interlayer exchange coupling between Gd and Co through Pt and Cr spacers in a series of multilayers. Magnetization curves have been analyzed with a model, taking into account bilinear and biquadratic interlayer exchange couplings between Gd and Co. The interlayer exchange coupling constants have been determined as a function of the Pt or Cr spacer layer thickness. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Multilayers; Interlayer exchange coupling; 4f–3d exchange coupling; Magnetization processes; Biquadratic exchange coupling

Interlayer exchange coupling (for a review see [1]) in magnetic multilayers is widely studied both for the large potentiality of commercial applications and for its fundamental interest. If magnetic films are separated by a metallic non-magnetic layer, the interlayer coupling has been observed to oscillate as a function of the spacer-layer thickness. The layers are coupled to each other by an exchange interaction via the electrons of the spacer layer, which has the same physical origin as the RKKY interaction between magnetic impurities. Interlayer coupling has been extensively investigated both in transition metal multilayers and in rare-earth multilayers and many theoretical models have been proposed: RKKY-based models [2] are more valid to describe magnetism in rare-earth multilayers, while other approaches such as free electrons models with exchange split bands [3] in ferromagnetic materials are more appropriate for transition metal multilayers. Most of the studies have been limited to the coupling between metals of the same type, either rare earths or transition metals. Only very few results [4–6] have been presented on exchange coupling between rare earth and transition metals. In intermetallic bulk materials it is well known that Gd (like other heavy rare earths) and Co are antiferromagnetically coupled. The aim of this study is to investigate the possible change of the sign of the coupling between Gd and Co layers in multilayer systems, as a function of the nature and the thickness of the spacer layer.

We have undertaken studies on the coupling between rare earth and transition metal through a metallic spacer in series of multilayers of type $[Gd/X/Co/X]_N$ with X = Pt, Cr. Several series of samples of different thicknesses were prepared by sputtering with Pt and Cr as spacer between cobalt and gadolinium layers. The samples were deposited at room temperature on silicon (1 0 0) substrates covered with a tungsten buffer layer (200 Å) from facing targets of pure metals (99.9%). The base pressure was 5×10^{-8} mbar and the deposit was done under an argon pressure of 3.5×10^{-3} mbar. A 200 Å-thick protective layer of tungsten was also deposited. The samples are polycrystalline. The whole thickness of each element was determined by Rutherford backscattering spectroscopy. We present in this paper some results on series of samples for which thicknesses are fixed around 16 Å for the Gd layers, 17 Å for the Co layers while the thickness of the spacer layer varies between 2 and 30 Å for Cr and Pt. The repetition number N was chosen to 14 to get a large enough magnetic moment to be measurable.

Magnetization measurements were performed in a vibrating sample magnetometer with an in-plane magnetic field up to 6 T at temperatures ranging from 10 and 300 K. Figs. 1–3 show typical examples of these measurements. Magnetization curves, such as those presented in Figs. 1 and 3 are obtained for thin Cr spacer

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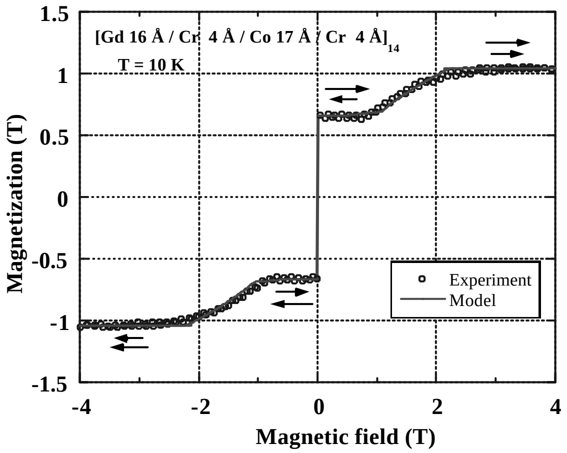

Fig. 1. Experimental and simulated magnetization curve, typical of a $[Gd/Cr/Co/Cr]_{14}$ multilayer with a small Cr thickness (4 Å).

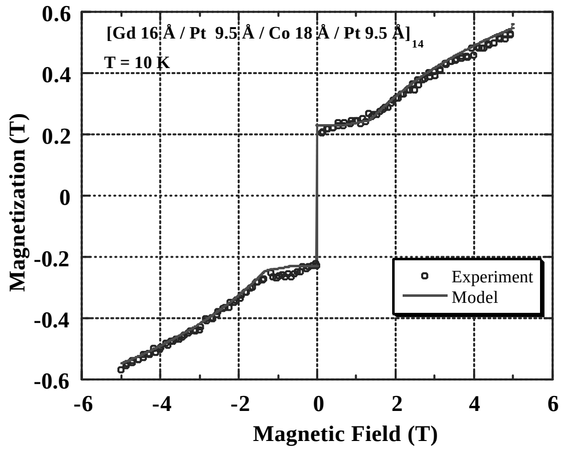

Fig. 3. Experimental and simulated magnetization curve, typical of a $[Gd/Pt/Co/Pt]_{14}$ multilayer with Pt spacer layer.

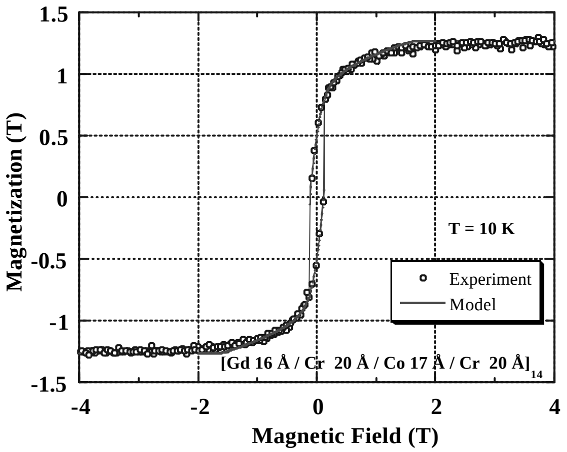

Fig. 2. Experimental and simulated magnetization curve, typical of a $[Gd/Cr/Co/Cr]_{14}$ multilayer with a large Cr thickness (20 Å).

layers up to ~8 Å and for samples with Pt spacer in the range of thicknesses presented in this paper. These curves present a transition as a function of applied magnetic field, which is the signature of an antiparallel coupling between Gd and Co. The value of the transition field H_t gives a measure of the interlayer coupling between the Co and Gd layers. The samples with Cr and Pt have different behaviors. For samples with chromium, the magnetization is constant in low field, which indicates a well collinear and antiferromagnetically coupled moments of Gd and Co. At a certain field, (~1 T for the sample of Fig. 1), a spin-flop transition occurs up to the field where saturation is clearly attained. The transition field decreases rapidly with the Cr layer thickness. Samples with Pt also present the spin flop transition but the magnetization increases slowly as a function of the applied field before the transition begins; and in high field the magnetization never seems to reach the saturation.

Fig. 2 shows a typical curve for a sample with large Cr thickness of (>10 Å). No spin-flop transition occurs. This behavior is more like ferromagnetic with the existence of hysteresis. In zero applied field, the Gd and Co moments are not aligned and a field (1.3 T in Fig. 2) is necessary to align the moments. This means that the indirect interlayer coupling does not tend to align the moments ferromagnetically or antiferromagnetically.

The determination of the strength of the coupling requires a model for the magnetization processes. We have developed a magnetic model taking into account all the energies of the real multilayer system and providing the magnetization curves and the magnetization profiles throughout the sample. The numerical simulations take into account the anisotropy of cobalt supposed to be uniaxial, the Zeeman energy, the demagnetizing field energy and the exchange energy. Considering the small thicknesses of the Gd and Co layers, we suppose that each layer of Gd(Co) is represented by a macrospin $\mathbf{M}_1$ ($\mathbf{M}_2$). The indirect exchange coupling between these macro-spins has the phenomenological form proposed by many authors [7,8]

$$E_{ij} = -J_1(\mathbf{m}_1.\mathbf{m}_2) - J_2(\mathbf{m}_1.\mathbf{m}_2)^2,$$

where $\mathbf{m}_1$ and $\mathbf{m}_2$ are the unit vectors of the macro-spins $\mathbf{M}_1$ and $\mathbf{M}_2$. The coefficient J_1 associated to the bilinear term represents the usual exchange term between two magnetic layers. A negative value of J_1 favors a collinear antiferromagnetic arrangement of $\mathbf{M}_1$ and $\mathbf{M}_2$, while a

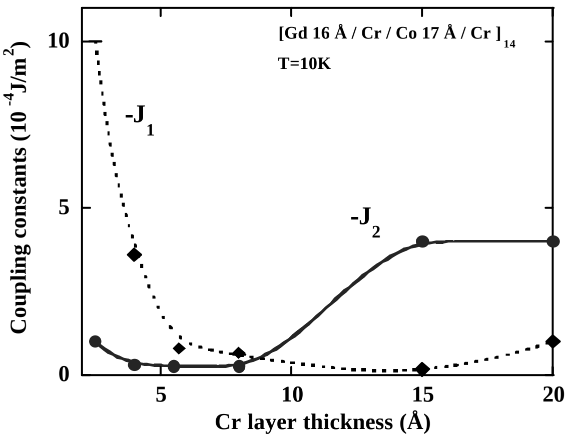

Fig. 4. Variation of the bilinear J_1 and biquadratic J_2 exchange coupling constants as a function of the Cr layer thickness, in a series of multilayers of type $[Gd/Cr/Co/Cr]_{14}$.

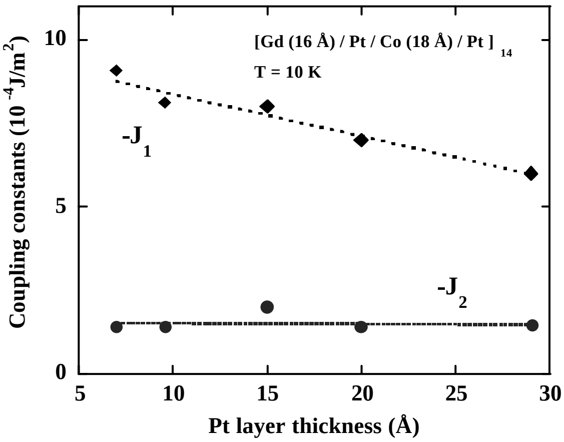

Fig. 5. Variation of the bilinear J_1 and biquadratic J_2 exchange coupling constants as a function of the Pt thickness, in a series of multilayers of type $[Gd/Cr/Co/Cr]_{14}$.

negative biquadratic term J_2 favors a non-collinear arrangement with 90° angles between the magnetic moments $\mathbf{M}_1$ and $\mathbf{M}_2$ of Gd and Co layers.

From the fit of the magnetization curves with this model it is possible to deduce the values of the exchange coupling J_1 and J_2 as a function of the spacer thickness. Figs. 4 and 5 show results for chromium and platinum. For low thicknesses of Cr, the bilinear term of coupling is sufficient to describe the magnetization curve while for larger thicknesses a biquadratic term is necessary. This means that for large Cr thicknesses the interlayer coupling yields a canted phase with an intermediate angle between the magnetic moments of Co and Gd layers. Accordingly, Fig. 4 shows a rapid decrease of the J_1 coefficient and a strong increase of the biquadratic term J_2 as a function of the Cr thickness. For the platinum spacer, the bilinear term J_1 is always much stronger than J_2 and decreases slightly with the Pt thickness as shown in the Fig. 5.

In summary, the interlayer coupling constants J_1 and J_2 between a gadolinium layer and a cobalt layer have been determined as a function of the spacer layer thickness for Pt and Cr spacers. Different behaviors have been evidenced due to the different magnetic states of Cr and Pt. Measurements of the polarization of platinum and chromium in trilayers Gd/X/Co with X = Cr or Pt by polarized neutron reflectometry are in progress.

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