Negative spin-valve effect in $Co_{65}Fe_{35}/Ag/(Co_{65}Fe_{35})_{50}Gd_{50}$ trilayers

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A minimum of the magnetoresistance under low fields has been observed with a $Co_{65}Fe_{35}/Ag/(Co_{65}Fe_{35})_{50}Gd_{50}$ trilayer at 4.2 and 300 K. This negative spin-valve effect is explained by the scattering of the conduction electrons by the Co or Fe moments included in two different structures: a polycrystalline ($Co_{65}Fe_{35}$) and an amorphous one [$(Co_{65}Fe_{35})_{50}Gd_{50}$]. The Gd moments allow one to control the magnetic configuration of the transition-metal moments of the layers but are inefficient for the magnetoresistance. This interpretation is confirmed by measurements using high pulsed fields.

INTRODUCTION

A large change of resistance ΔR with an applied field H of a multilayer made of magnetic transition metals (M) and nonmagnetic (NM) metals can be observed if the magnetic layers are coupled antiferromagnetically through the NM layer or, on the contrary, when they are uncoupled but possess different coercive fields.[1] Its resistance is then maximum when the M layers have an antiferromagnetic configuration and minimum when they present a ferromagnetic arrangement. This is due to spin-dependent scattering of conduction electrons by the magnetic layers. A large slope of ΔR versus H can be observed when the M layers possess an uniaxial anisotropy.[2] In the case of uncoupled M layers, different coercive fields can be obtained by coupling one of the layers with an adjacent antiferromagnetic layer,[3–5] or by using different magnetic alloys.[6–8]

The giant magnetoresistance (MR) effect obtained with $(Co_{65}Fe_{35})$/Ag granular alloys in a previous study[9] shows that $Co_{65}Fe_{35}$ and Ag are good candidates to study the spin-dependent scattering of conduction electrons. We have then been interested in MR effect of multilayers made with the same materials. $Co_{65}Fe_{35}$ has been alloyed with Gd to obtain a second magnetic layer with a lower coercive field.

The MR effect observed in $Co_{65}Fe_{35}/Ag/(Co_{65}Fe_{35})_{50}Gd_{50}$ trilayers is indeed a negative spin-valve effect since a minimum of resistance is observed in low fields. This can be explained by considering the antiferromagnetism of the $(Co_{65}Fe_{35})_{50}Gd_{50}$ alloy and by assuming that the conduction electrons are only scattered by Co or Fe moments.

EXPERIMENTAL DETAILS

The samples have been prepared by evaporation of $Co_{65}Fe_{35}$ alloy, Ag and Gd using an electron beam gun for $Co_{65}Fe_{35}$ and two Joule heating crucibles for Ag and Gd. The $(Co_{65}Fe_{35})_{50}Gd_{50}$ alloy has been prepared by coevaporation of $Co_{65}Fe_{35}$ and Gd. The deposited thickness was monitored with quartz oscillating sensors. The substrates consist of Corning glass or adhesive kapton pasted on glass. During the deposition, the substrate temperature was 20 °C and the pressure was less than 2×10^{-8} Torr. A 100-Å-thick amorphous layer of Si was first deposited at 150 °C on the substrates. All the samples were capped with a 200 Å Si layer deposited at 20 °C. The trilayers were deposited in the following order: Si buffer, $Co_{65}Fe_{35}$, Ag, $(Co_{65}Fe_{35})_{50}Gd_{50}$, Si.

The MR has been measured with a four-point probe method (dc current intensity: 1 mA), at room temperature with an electromagnet, and at 4.2 K with a superconducting coil cryostat. Magnetization measurements have been performed with a squid magnetometer with the same samples.

MAGNETIC PROPERTIES OF $(Co_{65}Fe_{35})_{50}Gd_{50}$ AND $Co_{65}Fe_{35}$ LAYERS

$Co_{1-x}Gd_x$ or $Fe_{1-x}Gd_x$ alloys prepared by coevaporation are antiferrimagnetic amorphous alloys with a Curie temperature steeply dependent on the concentration.[10] We have prepared a 100-Å-thick layer of $(Co_{65}Fe_{35})_{50}Gd_{50}$ deposited on glass with a buffer of amorphous Si, in the same condition as the multilayers. Its Curie temperature is 380 K and its magnetization measured at 5 K is $M=1100$ emu/cm^3. These values are reasonable with respect to those of $Co_{1-x}Gd_x$ or $Fe_{1-x}Gd_x$ alloys.[10]

This layer exhibits a uniaxial anisotropy as shown in Fig. 1(a). The easy axis lies in the plane of the sample and its direction is perpendicular to the plane including the incident directions of evaporated Co, Fe, and Gd. The anisotropy field H_a measured in the hard direction at 300 K [indicated by the arrow in Fig. 1(a)] is roughly 25 Oe. A detailed study of the anisotropy field of such alloys as a function of the angle of the incident flux of Co, Fe, and Gd will be published elsewhere.

A 100-Å-thick polycrystalline $Co_{65}Fe_{35}$ layer prepared by evaporation of $Co_{65}Fe_{35}$ exhibits also a uniaxial anisotropy in a direction perpendicular to the incident flux as shown in Fig. 1(b). The coercive field measured in the easy direction is 35

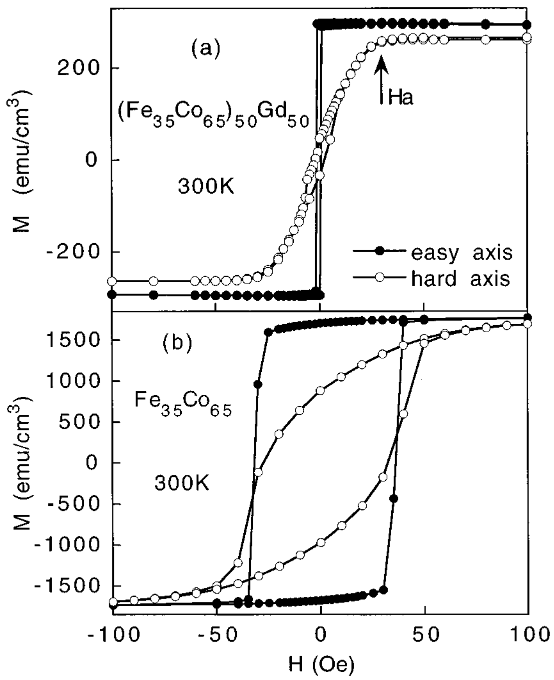

FIG. 1. Hysteresis cycles obtained at 300 K for 100 Å-thick amorphous $(Co_{65}Fe_{35})_{50}Gd_{50}$ (a) and polycrystalline $Co_{65}Fe_{35}$ (b) alloys deposited on amorphous Si (glass substrate).

Oe at 300 K. The origin of such anisotropy in evaporated magnetic layers is usually attributed to anisotropic grains growth or to magnetoelastic effect.[11] We point out that this uniaxial anisotropy has been observed here for amorphous and polycrystalline alloys; it has also been observed for a pure epitaxial metal.[12]

MAGNETORESISTANCE EFFECT

The magnetoresistance effect

$$\frac{\Delta R}{R_{\rm sat}}=\frac{R(H)-R(H_{\rm max})}{R(H_{\rm max})} \quad (H_{\rm max}=200\ \ {\rm Oe}),$$

measured with a current parallel to the easy axis at 4.2 K, is plotted in the field range $-150<H<150$ Oe in Fig. 2 for a

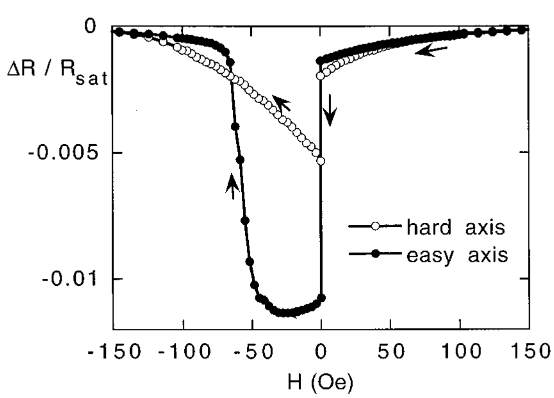

FIG. 2. Magnetoresistance effect $\Delta R/R_{\rm sat}$, where $R_{\rm sat}=R(H_{\rm max}=200$ Oe), measured at 4.2 K with a field applied along the easy and hard axis for a $Co_{65}Fe_{35}$/Ag/$(Co_{65}Fe_{35})_{50}Gd_{50}$ (100 Å/80 Å/100 Å) trilayer (glass substrate).

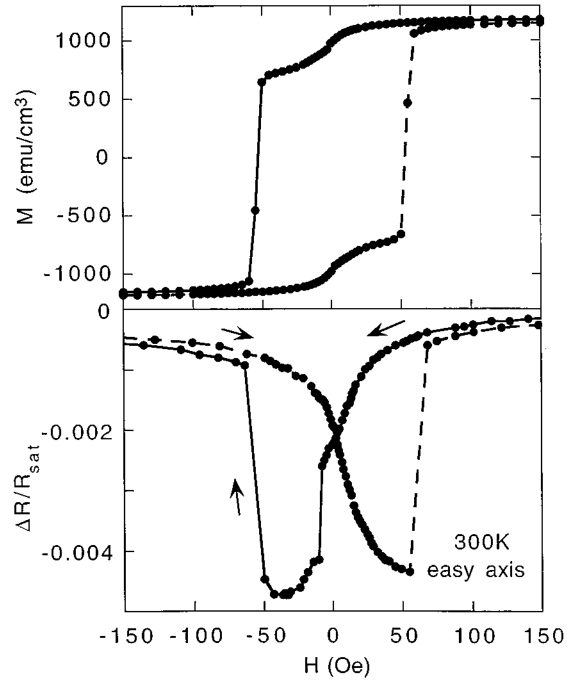

FIG. 3. Magnetoresistance effect $\Delta R/R_{\rm sat}$ with $R_{\rm sat}=R(H_{\rm max}=500$ Oe) and magnetization measured at 300 K with a field applied along the easy axis for a $Co_{65}Fe_{35}$/Ag/$(Co_{65}Fe_{35})_{50}Gd_{50}$ (100 Å/80 Å/100Å) trilayer (glass substrate).

$Co_{65}Fe_{35}$ (100 Å)/Ag(80 Å)/$(Co_{65}Fe_{35})_{50}Gd_{50}$(100 Å) trilayer. The field has been applied in the easy and in the hard directions of the magnetic layers. We observe in both directions a decrease of the resistance in the low-field range, of the order of 1% in the easy direction. This indicates that the change of resistance can be attributed to the scattering of Ag conduction electrons by the magnetic layers, and hence to a spin-valve effect; a change of resistance due to the anisotropic MR effect of transition metals would induce a negative or positive effect for an applied magnetic field, respectively, parallel or perpendicular to the measurement current, moreover, no significant MR effect has been observed with the single $(Co_{65}Fe_{35})_{50}Gd_{50}$ layer. To our knowledge, such a spin-valve effect between a polycrystalline and an amorphous layer has been only once observed before[8] with Co and CoFeB layers. The very steep decrease of resistance plotted in Fig. 2 for the longitudinal direction seems to occur for $H=0$. It indeed happens when the current source of the superconducting coil is reversed. This may induce the reversal of a remanent field which is of the order of 10 Oe.

The same MR effect is qualitatively recovered at 300 K as shown in Fig. 3 but its amplitude is significantly reduced. The correlation with magnetization confirms that the decrease of resistance, observed when the field is decreased from $H_{\rm max}$, is due to the reversal of the $(Co_{65}Fe_{35})_{50}Gd_{50}$ layer which has a smaller magnetization than the $Co_{65}Fe_{35}$ layer. We remark that the decrease of resistance and magnetization, corresponding to the reversal of the amorphous alloy, occurs for positive fields. This indicates the existence of a weak ferromagnetic coupling between the Co or Fe spins of the two layers which may be due to pinholes. It delays the reversal of the $Co_{65}Fe_{35}$ layer which has a coercive field ($\approx$50 Oe) larger than the coercive field of the single layer ($\approx$35 Oe).

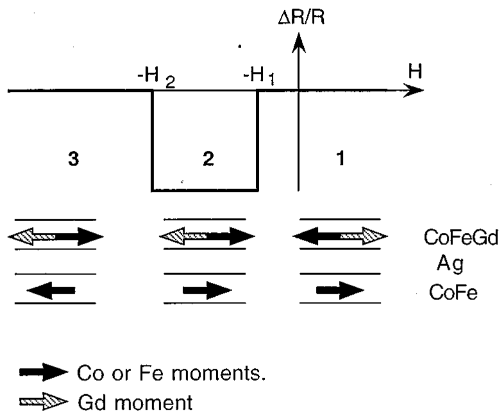

FIG. 4. Illustration of the negative spin-valve effect.

This peculiar field dependence of the resistance can be interpreted as a normal spin-valve effect, within the two currents model, assuming that the maximum of the resistance corresponds to an interaction of the conduction electrons with the two magnetic layers in an antiferromagnetic configuration. Moreover, if we assume that the conduction electrons interact only with Co or Fe moments, we obtain the theoretical field dependence of the resistance plotted in Fig. 4. In high positive fields (1), the dominant Gd moments of the $(Co_{65}Fe_{35})_{50}Gd_{50}$ alloy are aligned in the direction of the field. Because of their antiferromagnetic coupling with Gd moments, the Co or Fe moments of the amorphous layer are antiparallel to the field. The Co or Fe moments of the two layers are then antiferromagnetically stacked and the resistance is maximum. When the field is swept from positive to negative values, the moments of the transition metals of the two layers are in a ferromagnetic configuration between the coercive field $-H_1$ of the amorphous layer and the coercive field $-H_2$ of the $Co_{65}Fe_{35}$ layer (2). The resistance is then minimum. For a more negative field [lower than $-H_2$: (3)], the reversal of the magnetization of the $Co_{65}Fe_{35}$ alloy induces an increase of resistance.

Within the hypothesis of the exclusive interaction of conduction electrons with Co or Fe moments, the resistance is expected to reach its minimum value for very high fields able to destroy the antiferrimagnetism of the amorphous alloy and to align all the magnetic moments in the same direction. This is confirmed by the decrease of the resistance for magnetic fields up to 350 kOe (Fig. 5).

Actually, no spin-valve GMR effect has been observed with rare-earth ferromagnets. No spin-dependent scattering of conduction electrons is expected to take place in rare earth for which the split narrow $4f$ bands are usually far away from the Fermi level.[1] Moreover, one would expect the gadolinium to destroy the spin-valve effect, as it induces spin-orbit scattering of conduction electrons which can be depolarized, similarly to a temperature effect which leads to an increase of an intermixing of the spin ↑ and spin ↓ and to a decrease of the spin-valve amplitude. In our case, it seems that this spin-orbit scattering by the gadolinium moments does not significantly affect the observed negative spin-valve effect.

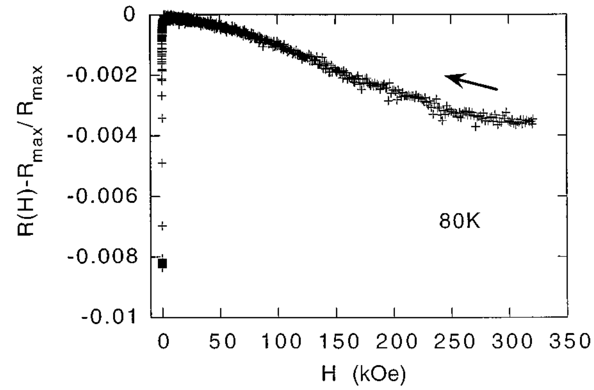

FIG. 5. Magnetoresistance effect $R(H)-R_{\max}/R_{\max}$ measured at 80 K with a pulsed high field applied along the easy axis for a $Co_{65}Fe_{35}/Ag/(Co_{65}Fe_{35})_{50}Gd_{50}$ (100 Å/40 Å/100 Å) trilayer deposited on a kapton substrate.

We point out that a minimum of the resistance for low fields has been already observed in spin-valve multilayers,[13,14] but its physical origin is nevertheless different. In that case, it corresponds to an inverse spin-valve effect induced by different spin-dependent scattering coefficients in the two magnetic layers, one stronger for spin-up electrons, the other stronger for spin-down electrons.

CONCLUSION

A negative spin-valve effect or a minimum resistance in low fields has been observed in $Co_{65}Fe_{35}/Ag/(Co_{65}Fe_{35})_{50}Gd_{50}$ trilayers. Thanks to the uniaxial anisotropy induced by the preparation mode, we observe abrupt changes of resistance which can be easily related to the reversal of the magnetization of the layers. The negative spin-valve effect can be explained by the scattering of Ag conduction electrons with exclusively Co or Fe moments included in a polycrystalline $(Co_{65}Fe_{35})$ and in an amorphous $[(Co_{65}Fe_{35})_{50}Gd_{50}]$ structure. The Gd moments are inefficient for the magnetoresistance effect but allow to change the magnetic configuration of the Co or Fe moments of the two layers in low fields.

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