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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 $\Delta R$ 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. 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 $\Delta R$ versus $H$ can be observed when the M layers possess an uniaxial anisotropy. In the case of uncoupled M layers, different coercive fields can be obtained by coupling one of the layers with an adjacent antiferromagnetic layer, or by using different magnetic alloys.

The giant magnetoresistance (MR) effect obtained with (Co$_{65}$Fe$_{35}$)/Ag granular alloys in a previous study 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 $2 \times 10^{-8}$ 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 antiferromagnetic amorphous alloys with a Curie temperature steeply dependent on the concentration. 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.

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
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

\[
\Delta R / R_{sat} = \frac{R(H) - R(H_{max})}{R(H_{max})}, \quad (H_{max} = 200 \text{ Oe}),
\]

measured with a current parallel to the easy axis at 4.2 K, is plotted in the field range \(-150 < H < 150 \text{ Oe}\) in Fig. 2 for a

\[\text{[Diagram]}\]

FIG. 2. Magnetoresistance effect \(\Delta R / R_{sat}\), where \(R_{sat} = R(H_{max} = 200 \text{ Oe})\), measured at 4.2 K with a field applied along the easy and hard axis for a Co\(_{65}\)Fe\(_{35}\)/Ag/(Co\(_{63}\)Fe\(_{33}\))\(_{50}\)Gd\(_{50}\) (100 Å/80 Å/100 Å) trilayer (glass substrate).

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 \(\text{Co}_{63}\)Fe\(_{35}\)/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 \(H_{max}\), is due to the reversal of the \(\text{Co}_{63}\)Fe\(_{35}\)/Gd\(_{50}\) layer which has a smaller magnetization than the \(\text{Co}_{63}\)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 \(\text{Co}_{63}\)Fe\(_{35}\) layer which has a coercive field (=50 Oe) larger than the coercive field of the single layer (=35 Oe).

\[\text{[Diagram]}\]

FIG. 3. Magnetoresistance effect \(\Delta R / R_{sat}\) with \(R_{sat} = R(H_{max} = 500 \text{ Oe})\) and magnetization measured at 300 K with a field applied along the easy axis for a Co\(_{63}\)Fe\(_{35}\)/Ag/(Co\(_{63}\)Fe\(_{33}\))\(_{50}\)Gd\(_{50}\) (100 Å/80 Å/100 Å) trilayer (glass substrate).
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, the dominant Gd moments of the (Co$_{68}$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. Moreover, if we assume that the conduction electrons with Co or Fe moments, the resistance is interpreted as a normal spin-valve effect, within the two currents model, assuming that the maximum of the resistance is expected to take place in rare earth with Co or Fe moments included. This peculiar field dependence of the resistance can be explained by the scattering of Ag conduction electrons with exclusively Co or Fe moments included. 

CONCLUSION

A negative spin-valve effect or a minimum resistance in low fields has been observed in Co$_{68}$Fe$_{35}$/Ag/(Co$_{68}$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$_{68}$Fe$_{35}$) and in an amorphous [(Co$_{68}$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.