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Spin-polarized current induced switching in Co/Cu/Co pillars

J. Grollier, V. Cros, A. Hamzic,[a] J. M. George, H. Jaffrès, and A. Fert
Unité Mixte de Physique CNRS/Thales,[b] 91404 Domaine de Corbeville, Orsay, France

G. Faini
LPN-CNRS, 196 av. H. Ravera, 92225 Bagneux, France

J. Ben Youssef and H. Legall
Laboratoire de Magnétisme de Bretagne-CNRS, 29285 Brest, France

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We present experiments of magnetization reversal by spin injection performed on pillar-shaped Co/Cu/Co trilayers. The pillars ($200\times600\,\mathrm{nm}^2$) are fabricated by electron beam lithography and reactive ion etching. Our data for the magnetization reversal at a threshold current confirm previous results on similar pillars. In addition, we present another type of experiment that also clearly evidences the control of the magnetic configuration by the current intensity. Our interpretation is based on a version of the Slonczewski model in which the polarization of the current is calculated in the Valet–Fert model of the giant magnetoresistance with current applied perpendicular to plane. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1374230]

The magnetization of a thin film can be reversed by spin transfer from a spin polarized current injected into the film. This effect has been predicted by Slonczewski[1] and confirmed by several recent experiments.[1–6] In measurements on submicron Co/Cu/Co pillars, Katine *et al.*[5] and Albert *et al.*[6] clearly observed magnetization reversals at current densities between 10^7 and $10^8\,\mathrm{A/cm}^2$. As already emphasized in the first article of Slonczewski, such magnetization reversals by spin injection should be of great interest for application to the switching of magnetic nanodevices, MRAM for example. The present challenging objective is the reduction of the required current densities and this probably goes through a better understanding of the involved physical mechanisms. How the current acts on magnetization is still a controversial point. Several types of models have been developed,[7–11] some of them describing the effect of the current by an effective exchange interaction between magnetic layers.[10]

In this letter, we describe experimental results on submicron Co/Cu/Co pillars fabricated in the following way. First the bottom electrode is patterned by an electron beam lithography (EBL) using a JEOL 5DIIU writer with subsequent lift-off of a 250 Å thick Au layer deposited by electron beam evaporation. After deposition of a 1000 Å thick SiC insulating layer, the templates for the pillars are fabricated by combining EBL and reactive ion etching. In order to perform a self-aligned technique, the PMMA resist used in this step is conserved to process afterward by lift-off of the Co/Cu/Co pillar deposited by sputtering. Finally, we pattern a Au upper electrode isolated from the bottom electrode by the SiC layer. The pillars have various shapes from 100×100 to $200\times600\,\mathrm{nm}^2$.

The experimental results described below have been obtained on pillars of $200\times600\,\mathrm{nm}^2$ and with trilayers composed of a thick Co layer (Co1=15 nm) and a thin Co layer (Co2=2.5 nm) separated by a 10 nm Cu layer [Fig. 1(b)]. A dc current is passed through the pillar to switch the magnetic configuration of the trilayer and the change of resistance (GMR effect) is used to detect the switching. The resistance is measured with a standard four contact probes technique. A magnetic field can be applied along the long side of the rectangular pillar. In Fig. 2(a) we show an example of a CPP–GMR curve obtained with a small current of 50 μA. The magnetoresistance is small ($\approx 0.5\%$), which is due to the relatively small contribution of the Co/Cu/Co trilayer to the total resistance of the pillar. However, the typical features of GMR are clearly observed, with well defined field ranges for the P and AP configurations (P=parallel, bottom line; AP=antiparallel, after reversal of the thick Co layer and before reversal of the thin one). In order to study the reversal of magnetization induced by an increase of the current, it is important to know precisely the initial configuration before the current is increased. In the experiments described here, after saturating the magnetization in a positive (negative) field of 5500 Oe, and then decreasing (increasing) the field to zero, we started from the A (or A^*) point on the GMR curve of Fig. 1(a). These starting points correspond to a P configuration with the magnetizations of the two Co layers parallel to the direction of positive (negative) fields. Figure 1(c) shows the variation of the resistance (R) versus the injected dc current (I) obtained on the same pillar at zero field. Starting from the P configuration at A in Fig. 1(a), we increase or decrease the current (in our notation, positive I means electrons going from the thick Co layer to the thin one).

For $I>0$, nothing occurs except a gradual and reversible rise of R along a curve that we call $R_P(I)$. This rise, as in the data reported by Katine *et al.*,[5] can be attributed to some enhancement of the hot electrons scattering. For $I<0$, the system first moves reversibly along $R_P(I)$ and then jumps into a high resistance state at a critical current that we call I_c^P, where $I_c^P\approx-15\,\mathrm{mA}$. After the jump, when I varies be-

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[a] On leave from the Department of Physics, Faculty of Science, HR-1000 Zagreb, Croatia.

[b] UMR 137 du CNRS, associated to the University Paris-Sud, 91405 Orsay Cedex, France.

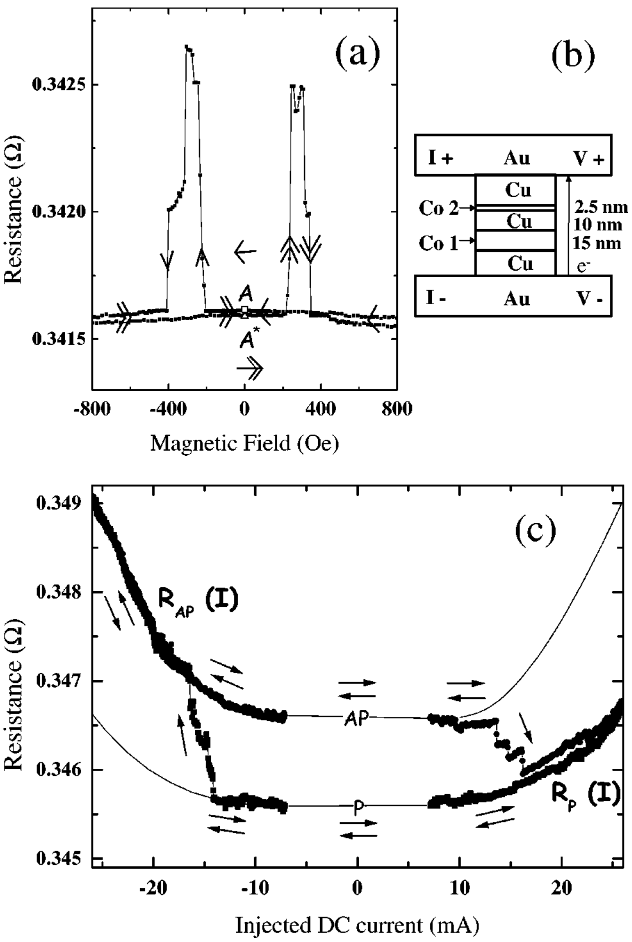

FIG. 1. (a) GMR curve of a 200×600 nm^2 Co/Cu/Co pillar at 30 K with $I = 50\,\mu$A; (b) schematic of a pillar; (c) resistance as a function of current. Single arrows (double arrows) indicate the irreversible (reversible) parts of the cycle. The measurements at low current (flat part of the variation) were noisy for technical reasons and have been omitted from the figure. The thin lines have been obtained by symmetry and are guides for the extrapolation of $R_{AP}(I)$ and $R_P(I)$.

tween its maximum negative value and about $+15$ mA, the system moves reversibly on a high resistance curve that we name $R_{AP}(I)$. When I exceeds a critical current $I_c^{AP} \approx +15$ mA, the resistance drops back onto the $R_P(I)$ curve [actually, on the curve of Fig. 1(c), this drop is composed of several successive jumps].

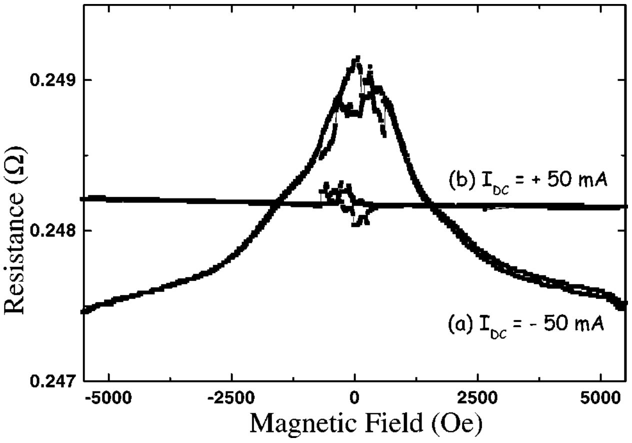

FIG. 2. Resistance as a function of the applied field for a 200×600 nm^2 pillar (sample 2). The current is: -50 mA for curve (a) and $+50$ mA for (b).

The difference of about 1 mΩ between $R_{AP}(I)$ and $R_P(I)$ corresponds approximately to the amplitude of the GMR for small ac current. This indicates that the system is switched from P to AP at I_c^P and from AP to P at I_c^{AP}. This switching is due to the reversal of the moment of the thin Co layer, in agreement with what can be expected in the Slonczewski model from the effect of torques on two magnetic layers with not very different coercive fields and very different thicknesses. The same clockwise $R(I)$ loops are found when we start from $A*$. When the experiments described in Fig. 1(c) are performed with a positive magnetic field, i.e., the field is applied in the direction of the magnetizations in the initial configuration A, $|I_c^P|$ increases and I_c^{AP} decreases, as expected from a stabilization of the parallel configuration by an applied field. At high enough field (above 5 kOe), the trilayer is still pinned in the P configuration at our highest current value and the background curve $R_P(I)$ can be recorded throughout the whole experimental range of I.

The described behavior and, in particular, the asymmetric action of positive and negative currents is in agreement with the Slonczewski model[1] and also with the more recent models[10] expressing the effect of the current by an effective interaction which, depending on the sign of the current, is ferromagnetic- or antiferromagnetic-like. Our results are also quite similar to the previous ones on pillars obtained at Cornell University[5,6] (we point out the opposite conventions for the sign of I in Katine *et al.*[5] and in this letter). An essential feature is that, regardless of the initial configuration (A or $A*$ for example), the switching from P to AP is always induced by a negative current. On the other hand, only a positive current can switch from AP to P. This definitely distinguishes the magnetization reversal by spin injection from the possible reversal by the magnetic field generated by the current. Actually, in the latter case, the reversal from P to AP for example, can be obtained either with positive or negative current depending on the direction of the moments in the P arrangement. This gives the symmetric $R(H)$ curves as found for the multilayered pillars.[12,13] However, even if the driving mechanism of the switching in our experiments is clearly spin injection, some additional influence of the field generated by the current cannot be completely ruled out.

Figure 2 presents another type of experimental approach in which we sweep the magnetic field between -5.5 and $+5.5$ kOe keeping the current constant. For $I = -50$ mA, the split peaks of the low current GMR curve are replaced by a reversible and much broader peak extending from approximately -3000 to $+3000$ Oe, so that the MR curve looks like the GMR curve for a trilayer with a strong antiferromagnetic coupling. On the contrary, with $I = +50$ mA, the GMR effect disappears and $R(I)$ is a horizontal flat line, as expected for a ferromagnetic coupling. Does this mean that the effect of the current must be described by an effective interaction between the magnetic moments of the two layers, as predicted by Heide *et al.*?[10] As a matter of fact, the results of Fig. 2 are consistent with both the interaction picture and Slonczewski's model. For example, the curve with $I = -50$ mA can be described within the Slonczewski model as follows: starting from a parallel configuration at $H = +5.5$ kOe and decreasing sufficiently the field, the negative current reverses the magnetization of the thin Co layer and the configuration becomes AP, in agreement with the resistance rise in the peak. Then, in turn, the magnetization of the thick layer is reversed when the applied field becomes negative and exceeds H_c. Since the resulting P configuration is unstable in a negative current, the magnetization of the thin layer is also reversed and the system practically remains in its AP configuration. Finally a sufficient negative field induces again a P configuration and the resistance drops back to its initial value. We conclude that, at this stage, our experimental results do not allow us to decide between the Slonczewski and interaction pictures. We now present a quantitative fit of our results with the Slonczewski model.[1] A first difficulty comes from the asymmetry between I_c^P and I_c^{AP} at $H=0$. In Slonczewski's model, the dependence of the spin currents on the angle θ between the moments of the two layers is calculated in a ballistic approach, which comes out with the factor $1/g(\theta)$ in the expression of the critical currents and leads to $|I_c^P| > |I_c^{AP}|$ [from $g(\pi) > g(0)$]. As we find approximately equal values of I_c^P and I_c^{AP}, we tried the following alternative approach. We replaced Slonczewski's calculation in a ballistic approach by a calculation of the current spin asymmetry in the Valet–Fert model of the diffusive CPP-GMR.[14] Details on the calculation of the current spin asymmetry in the thin Co layer for the P and AP configurations, P_I^P and P_I^{AP}, will be reported elsewhere. We present only the numerical results obtained by calculating P_I^P and P_I^{AP} from GMR data on Co/Cu multilayers and introducing P_I^P and P_I^{AP} in the expressions of the critical currents I_c^P and I_c^{AP}:

$$I_c^{AP}(I_c^P) = +(-)eMA[2\pi M + (-)H]\alpha t/hP_I^{(AP)P}. \quad (1)$$

In Eq. (1), M is the magnetization, H is the magnetic field, t is the thickness of the thin layer, α is the Gilbert coefficient, and A is the area of the pillar. By introducing in the Valet–Fert model the values for the resistivity of the Cu and Co layers found by Bass and Pratt[15] in Co/Cu multilayers, the resistance of the Co/Cu interfaces, the spin asymmetry coefficients β and γ and the spin diffusion length (SDL) in Cu, as well as the SDL in Co layers derived by Fert and Piraux,[16] we obtain $P_I^P = 0.26$ and $P_I^{AP} = 0.075$. By using these polarization values in Eq. (1) with $M = 1420\,\text{emu/cm}^3$ and $\alpha = 0.007$,[17] we obtain for the critical currents in zero field: $I_c^P \approx -15\,\text{mA}$ (current density $\approx 1.2\times10^7\,\text{A/cm}^2$) and $I_c^{AP} \approx +55\,\text{mA}$ (current density $\approx 4.5\times10^7\,\text{A/cm}^2$).

As the critical current densities at zero field in our experiments are about $10^7\,\text{A/cm}^2$, we first point out that the Slonczewski model predicts very correctly the order of magnitude of the critical current. On the other hand, we see that, by replacing the ballistic approach of Slonczewski by a model of CPP-GMR for the calculation of the current spin polarization, the asymmetry between the critical currents is reversed. In other words, the calculation gives $|I_c^{AP}| > |I_c^P|$. This is in agreement with the experimental results shown by Albert *et al.*[6] but not with our experimental finding of approximately equal absolute values of the critical currents. Another point of discrepancy is also the field dependence of the critical currents. For example, in the case of I_c^P for which the above calculation reproduces correctly the experimental value, the field dependence calculated with the same parameters is too small by about a factor five. The same difficulty to fit the zero field value of the critical currents and their field dependence has been found by Katine *et al.*[5]

In conclusion, our experimental results on magnetic switching by spin injection in pillar-shaped Co/Cu/Co trilayers, in agreement with the previous results by the Cornell group,[5,6] confirm the theoretical predictions of current driven interlayer coupling. In addition to the $R(I)$ measurements, we have presented another type of experiment (Fig. 2) in which the influence of the current intensity on the $R(H)$ curve evidences clearly the control of the magnetic configuration by the current injection intensity. We have also developed an interpretation of our results by mixing Slonczewski's equations with a calculation of the current spin polarization based on the Valet–Fert model of CPP-GMR.[14] This calculation predicts critical currents of the right order of magnitude. However, there is some discrepancy between the calculation and experiments for the asymmetry between the critical currents I_c^P and I_c^{AP} and for their field dependence. Other experiments are in progress to analyze the influence of the layer thickness and to get to the relevant scaling length of the system. Specific tests aimed at deciding between the several existing types of model[1,7–11] are also planned.

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