Current-Induced Two-Level Fluctuations in Pseudo-Spin-Valve (Co/Cu/Co) Nanostructures

A. Fábián, C. Terrier, S. Serrano Guisan, X. Hoffer, M. Dubey, L. Gravier, and J.-Ph. Ansermet
Institut de Physique des Nanostructures, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

J.-E. Wegrowe
École Polytechnique, Laboratoire des Solides Irradiés, F-91128 Palaiseau CEDEX, France
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Two-level fluctuations of the magnetization state of pseudo-spin-valve pillars Co(10 nm)/Cu(10 nm)/Co(30 nm) embedded in electrodeposited nanowires ($\sim$40 nm in diameter, 6000 nm in length) are triggered by spin-polarized currents of 10^7 A/cm^2 at room temperature. The statistical properties of the residence times in the parallel and antiparallel magnetization states reveal two effects with qualitatively different dependences on current intensity. The current appears to have the effect of a field determined as the bias field required to equalize these times. The bias field changes sign when the current polarity is reversed. At this field, the effect of a current density of 10^7 A/cm^2 is to lower the mean time for switching down to the microsecond range. This effect is independent of the sign of the current and is interpreted in terms of an effective temperature for the magnetization.

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Current-induced magnetization switching (CIMS) was predicted by Slonczewski [1] after a first publication by Berger [2]. Observation of this phenomenon in several sample configurations was reported a few years later: homogeneous Ni nanowires [3], manganite trilayer junctions [4], and (Co/Cu/Co) sandwich structures [5–8]. The potential application of the latter structure as a nonvolatile magnetic memory motivates the development of detailed models for the theoretical mechanisms underlying CIMS. Most of the present models [9–13] agree on the fact that the Landau-Lifshitz-Gilbert (LLG) equation can be modified by a current-dependent term. This term acts either as a torque, an effective field, or leads to spin transfer by a relaxation process. Two experimental approaches are preferred: sweeping the magnetic field H or the applied current I in order to obtain $R(I)$, $R(H)$, $dV/dI(H)$, or $dV/dI(I)$. Alternatively, observations of the relaxation of the magnetization [14–16] provide information on the magnetic energy profile.

Recent experimental work showed that it is possible to produce two level fluctuation (TLF) in spin-valve nanostructures with the injection of a spin-polarized current [16,17]. In this paper, the TLF produced by the current are studied in pseudo-spin-valves and analyzed in terms of a potential profile composed of two wells separated by a barrier. The applied field can be adjusted so that the potential well is symmetrical. At this field, it becomes especially clear that the current enhances the jump rate irrespective of the current sense.

This study focuses on the irreversible part of the hysteresis in a (Co/Cu/Co) pseudo-spin-valve buried in the middle of a long Cu nanowire. A uniaxial magnetocrystalline anisotropy can be obtained [18]. Thus, the spin-valve behaves as a two-state system defined by the two relative orientations of the magnetic layers. The samples were produced by the method of electrodeposition in track-etched membrane templates [19]. Gold layers were sputtered on both sides of a porous polycarbonate membrane; the pores left open were filled electrochemically with Co and Cu. Wires of Cu(1000)/[Co(10)/Cu(10)/Co(30)]/Cu(4950), about 40 nm in diameter and 6000 nm in length, were obtained. A contact to a single nanowire was established by monitoring the potential between both sides of the membrane during the electrodeposition [20].

Experiments were performed at room temperature. For characterization purposes, giant magnetoresistance (GMR) of the spin-valve system was measured at low current ($\sim 10^4$ A/cm^2). The sample shape ensured current-perpendicular-to-the-plane (CPP) geometry. The magnetic field was applied in the direction parallel to the plane of the Co layers. The GMR results showed a hysteretic behavior with abrupt steps between two resistance values R^p and R^{ap} ($\Delta R = R^{ap} - R^p$ is typically 1 Ω or $\Delta R/R_{\mathrm{wire}} = 0.18\%$) corresponding to the switching of the relative magnetization orientation of the ferromagnetic layers (dashed lines in Fig. 1). The abrupt single transitions between these two orientations suggest single-domain structures.

Hysteresis measurements were also performed under large dc currents ($\sim 10^7$ A/cm^2). Large currents affect the field range over which the spin-valve is in the antiparallel state. This range increases with increasing positive currents I^+ [full line in Fig. 1(a)] and decreases with negative currents I^- [full line in Fig. 1(b)]. The positive current is defined as the one for which electrons flow from the thin to the thick magnetic layer (in contrast to the definition of Ref. [7]). For each current I^+ or I^-, we determined the magnetic field $H_{sw}^{p \to ap}$ at which a parallel to antiparallel transition occurred. The time-domain

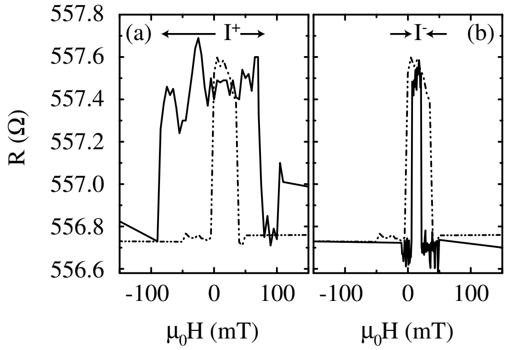

FIG. 1. (a) Hysteresis half cycle at large positive current (full line) and low current (dashed line). (b) Hysteresis half cycle at large negative current (full line) and low current (dashed line). Positive current: Electrons flow from the thin to the thick layer.

measurements were carried out as follows. A saturation field of 1 T was established and swept down with a rate of 0.05 T/s to the measurement field H in the vicinity of $H_{sw}^{p\rightarrow ap}$. At this field value H, a current pulse was applied, of amplitude I and of 8 μs duration. The resistance was recorded as a function of time. For a broad range of applied fields, the spin-valve system presented TLF between R^p and R^{ap} (Fig. 2). The apparent intermediate steps in Fig. 1 as well as the fluctuations that appear in Fig. 2 are nothing but noise. The stochastic nature of this process was assessed by determining the histograms of the residence times τ_{ap} or τ_p before each transition. They presented an exponential distribution (inset of Fig. 2) from which the characteristic times $\langle\tau_{ap}\rangle$ and $\langle\tau_p\rangle$ could be extracted.

For each current value, the protocol was repeated for several values of H until H was so far from $H_{sw}^{p\rightarrow ap}$ that the fluctuations were too scarce. This measurement process was repeated for several current values (either positive or negative). This protocol and the measurement setup implies two limiting currents: The lowest current is the one that allows the observation of at least one magnetization switching ($p \rightarrow ap \rightarrow p$) in the interval time of 8 μs, and the highest current is the one for which the switching rate is below the bandwidth of the measurement setup, 25 MHz. We collected data of average times versus field and current $\langle\tau_p\rangle/\langle\tau_{ap}\rangle$ (Fig. 3) at fields around the $p \rightarrow ap$ transition seen in the high current GMR curves (Fig. 1). We have carried out a detailed study of the TLF around the transition $H_{sw}^{p\rightarrow ap}$.

We can assume that the thick Co layer remains fixed because we restricted the magnetic field values to a small enough range. The metastable characteristics of the magnetization of the thin Co layer can be described by the Néel-Brown activation process [21]. The energy barrier depends on the shape and magnetocrystalline anisotropy, on the external field, and on the dipole field due to the pinned layer [18]. At low current, the spin-valve is stable and does not show TLF. The effective barrier when the double well is symmetric can be estimated to be of the order of several thousands Kelvin [22]. Therefore the TLF at large current cannot be ascribed to Joule heating and must arise from spin polarization of the current.

The mean time to escape from a local energy minimum i over an effective barrier into another local minimum j, where $\{i, j\} = \{p, ap\}$ or $\{ap, p\}$ (inset of Fig. 4), can be written in the form of a Néel-Brown law [23]:

$$\tau_i = \tau_0 \exp\left(\frac{E^{i\rightarrow j}(H)}{k_B T}\right), \tag{1}$$

where $E^{i\rightarrow j}$ is the energy maximum of the barrier measured from the local minimum i, and τ_0 is the waiting time at zero energy barrier. The value of τ_0 we choose is not critical for the outcome of our analysis. We set it at $\tau_0 \sim 0.1$ ns as a reasonable order of magnitude.

We report in Fig. 4 the value of the magnetic field $H_{\rm sym}(I)$ applied at each current I in order to obtain a symmetric profile, that is, when $\langle\tau_{ap}\rangle/\langle\tau_p\rangle = 1$. The bias field necessary to make the magnetic potential well symmetric is a monotonic, almost linear function of the current. Here, the effect of a positive current appears as a

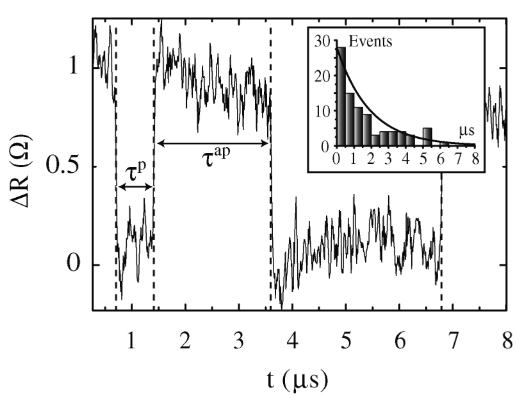

FIG. 2. Time-resolved response of an applied current of 8 μs duration. Inset: typical histogram of the residence times τ_{ap} or τ_p.

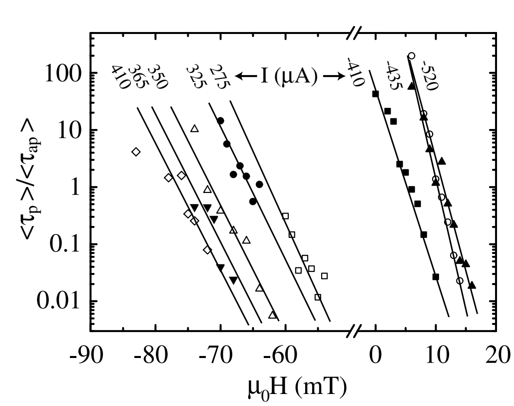

FIG. 3. Ratio $\langle\tau_p\rangle/\langle\tau_{ap}\rangle$ vs magnetic field for different applied currents.

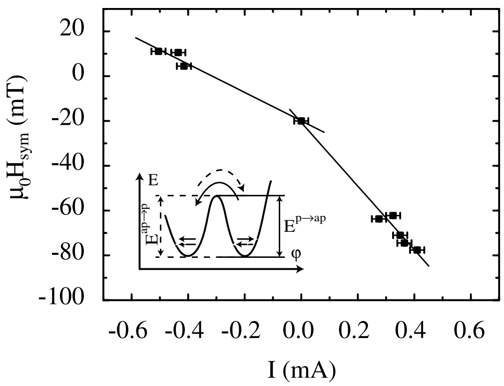

FIG. 4. External magnetic field $H_{sym}(I)$ vs applied current I at which $\langle\tau_{ap}\rangle = \langle\tau_p\rangle$. Inset: schematic view of the potential profile, where φ represents the relative magnetization orientation of the Co layers. Straight lines are a guide for the eye.

positive bias field, since a negative field must be applied to compensate for it so as to keep the well symmetric. A positive bias field corresponds to a tendency to remain in the antiparallel state. This is equivalent to the hysteresis widening of Fig. 1.

Our data show that the effect of the current is not simply a biasing of the potential profile. We find that, at the field $H_{sym}(I)$, the mean time $\langle\tau_{ap}\rangle = \langle\tau_p\rangle$ decreases with the absolute value of the current as shown in Fig. 5. Hence, this effect is qualitatively different than the dependence $H_{sym}(I)$.

We discuss now the possible interpretations that may account for our observations of $H_{sym}(I)$ and $\langle\tau_{ap}\rangle(I)$ when $\langle\tau_{ap}\rangle = \langle\tau_p\rangle$. Assuming the injection of spin-polarized current [1], the LLG equation can be written as [24]

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M}\times\boldsymbol{H}_{\mathrm{eff}} + \frac{\alpha}{M_s}\boldsymbol{M}\times\frac{d\boldsymbol{M}}{dt} + \frac{\gamma a_J}{M_s}\boldsymbol{M} \times (\boldsymbol{M}\times\hat{\boldsymbol{M}}_p), \qquad (2)$$

where $\boldsymbol{M}$ is the magnetization of the free layer, γ is the gyromagnetic factor, $\boldsymbol{H}_{\mathrm{eff}}$ is the effective field, including the applied field, anisotropy field, demagnetizing field, and random fields (caused by thermal fluctuations), α is the Gilbert damping factor, M_s is the magnetization value at saturation, a_J is the dependence of the current-driven torque on the applied current, and $\hat{\boldsymbol{M}}_p$ is a unit vector representing the magnetization orientation of the pinned layer. It has been shown that the Néel-Brown relaxation formula can be applied by introducing an activation energy defined as the difference between the true energy barrier and the work done by the current-driven torque [24]. Depending on the current, this work can be either positive or negative. This point of view fits with our observation of $H_{sym}(I)$ which is positive or negative depending on the polarity. However, this model cannot account for the positive slope at negative current (Fig. 5). Therefore we need to turn to another mechanism to explain $\langle\tau_{ap}\rangle(I)$ when $\langle\tau_{ap}\rangle = \langle\tau_p\rangle$.

Several authors have considered the excitation of spin waves by current [25,26]. Here, we estimate the effect of the excitation of spin waves caused by the injection of spin-polarized currents in terms of an effective magnetization temperature, an idea simultaneously raised by Urazhdin *et al.* [17]. Electrons are injected in the thin layer with a polarization β. Spins of electrons with s character are rapidly relaxed via spin-orbit scattering, while spins of d electrons relax as the magnetization. Each d electron carries one Bohr magneton whose relaxation produces, on average, the equivalent of one magnon. Hence, the time rate of generation of magnons by a current I is counted to be $\alpha_d\beta(I/e)$, where α_d is thought of as a coefficient between 0 and 1 that represents the proportion of d-type conduction electrons. In the order of magnitude estimate below, we take $\alpha_d = 4\%$, $\beta(I > 0) = 40\%$, and $\beta(I < 0) = 27\%$. The dependence of β on the sense of the current can be expected since the spin-valve is asymmetric [13].

Magnetic resonance studies of the bottleneck effect [27,28] tell us that d electrons relax on a time scale τ_d of the order of 1 ns. So the average number of magnons follows a rate equation:

$$\frac{dn}{dt} = -\frac{n}{\tau_d}. \qquad (3)$$

The current pulse is very long compared to magnetization dynamics. Since we detect TLF over a time scale of microseconds, the magnetic excitations have reached a stationary state out of equilibrium. The average number of magnons is the one that balances the generation of magnons by the current and their relaxation to the lattice:

$$\frac{n}{\tau_d} = \alpha_d\beta\frac{I}{e}. \qquad (4)$$

The average number of spin waves at a temperature T_m follows a Bose-Einstein distribution $[\exp(\hbar\omega/k_B T_m) - 1]^{-1}$. Taking the spin wave dispersion relation $\hbar\omega(k) \approx 2JSa^2 \cdot k^2$, where $\boldsymbol{k}$ is the wave vector and a is the lattice

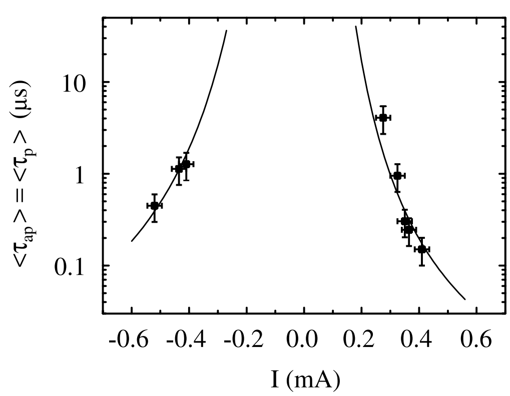

FIG. 5. Mean time $\langle\tau_{ap}\rangle = \langle\tau_p\rangle$ as a function of the current I at the field $H_{sym}(I)$. Line: prediction of Eqs. (4)–(6) with parameters as indicated in the text.

constant, the density of magnons at this temperature can be estimated from [29]

$$\frac{1}{V}\sum_k \langle n_k \rangle = \frac{1}{(2\pi)^2}\left(\frac{k_B T_m}{2JSa^2}\right)^{3/2}\frac{1}{2}\sqrt{\pi}\zeta(3/2), \qquad (5)$$

where the stiffness constant $2JSa^2$ is of the order of 5 meV nm^2 for Co, and the zeta function $\zeta(3/2) = 2.61$. We can account for the data of Fig. 5 by assuming that this random, incoherent generation of magnons gives rise to a magnetic state of excitation characterized by a temperature T_m calculated with Eqs. (4) and (5). The mean times are assumed to follow

$$\langle \tau_{ap} \rangle(I) = \langle \tau_p \rangle(I) = \tau_0 \exp\left(\frac{E_0}{k_B T_m(I)}\right), \qquad (6)$$

with $E_0 = 6'300$ K, a reasonable value for a Co layer of this size [22]. Thus, we can account for our data (Fig. 5) with a variation of the effective temperature $T_m(I)$ from about 500 to 1100 K.

In conclusion, we have measured the current dependence of the magnetic energy profile of a (Co/Cu/Co) nanopillar. Positive current shifts the field range over which the TLF zone is seen to more positive magnetic fields, while negative current shifts it to more negative fields. However, both current directions decrease the jump rate. Consequently, these two qualitatively different features cannot be accounted for with a current-dependent effective torque only. Instead, it appears that an irreversible transfer of magnetic momentum occurs, leading to spin wave excitations.

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[1] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[2] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[3] J.-E. Wegrowe, D. Kelly, Y. Jaccard, P. Guittienne, and J.-P. Ansermet, Europhys. Lett. **45**, 626 (1999).
[4] J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).
[5] E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, Science **285**, 867 (1999).
[6] M. Tsoi, A. G. M. Jansen, J. Bass, W. C. Chiang, M. Seck, V. Tsoi, and P. Wyder, Phys. Rev. Lett. **80**, 4281 (1998).
[7] J. Grollier, V. Cros, A. Hamzic, J. M. George, H. Jaffrès, A. Fert, G. Faini, J. Ben Youssef, and H. Legall, Appl. Phys. Lett. **78**, 3663 (2001).
[8] J. Z. Sun, D. J. Monsma, D.W. Abraham, M. J. Rooks, and R. H. Koch, Appl. Phys. Lett. **81**, 2202 (2002).
[9] X. Waintal, E. B. Myers, P.W. Brouwer, and D. C. Ralph, Phys. Rev. B **62**, 12 317 (2000).
[10] C. Heide, Phys. Rev. Lett. **87**, 197201 (2001).
[11] J.-E. Wegrowe, Phys. Rev. B **62**, 1067 (2000).
[12] J. Grollier, V. Cros, H. Jaffrès, A. Hamzic, J. M. George, G. Faini, J. Ben Youssef, H. Le Gall, and A. Fert, Phys. Rev. B **67**, 174402 (2003).
[13] S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002).
[14] J.-E. Wegrowe, X. Hoffer, P. Guittienne, A. Fábián, L. Gravier, T. Wade, and J.-P. Ansermet, J. Appl. Phys. **91**, 6806 (2002).
[15] F. J. Albert, N. C. Emley, E. B. Myers, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **89**, 226802 (2002).
[16] E. B. Myers, F. J. Albert, J. C. Sankey, E. Bonet, R. A. Buhrman, and D. Ralph, Phys. Rev. Lett. **89**, 196801 (2002).
[17] S. Urazhdin, H. Kurt, W. P. Pratt, Jr., and J. Bass, Appl. Phys. Lett. **83**, 114 (2003); S. Urazhdin, N. O. Birge , W. P. Pratt, Jr., and J. Bass, Phys. Rev. Lett. **91**, 146803 (2003).
[18] J.-E. Wegrowe, A. Fábián, P. Guittienne, X. Hoffer, D. Kelly, J.-P. Ansermet, and E. Olive, Appl. Phys. Lett. **80**, 3775 (2002).
[19] A. Fert and L. Piraux, J. Magn. Magn. Mater. **200**, 338 (1999).
[20] J.-E. Wegrowe, S. E. Gilbert, D. Kelly, B. Doudin, and J.-P. Ansermet, IEEE Trans. Magn. **34**, 903 (1998).
[21] W. Coffey, Y. P. Kalmykov, and J. T. Waldron, *"The" Langevin Equation*, Contemporary Chemical Physics Vol. 11 (World Scientific, Singapore, 1998).
[22] W. Wernsdorfer, K. Hasselbach, A. Benoit, G. Cernicchiaro, D. Mailly, B. Barbara, and L. Thomas, J. Magn. Magn. Mater. **151**, 38 (1995).
[23] W. T. Coffey, D. S. F. Crothers, J. L. Dormann, Y. P. Kalmykov, E. C. Kennedy, and W. Wernsdorfer, Phys. Rev. Lett. **80**, 5655 (1998).
[24] Z. Li and S. Zhang, arXiv:cond-mat/0302339.
[25] M. Tsoi, V. Tsoi, J. Bass, A. G. M. Jansen, and P. Wyder, Phys. Rev. Lett. **89**, 246803 (2002).
[26] S. M. Rezende, F. M. de Aguiar, M. A. Lucena, and A. Azevedo, Phys. Rev. Lett. **84**, 4212 (2000).
[27] N. Bloembergen, Phys. Rev. **78**, 572 (1950).
[28] C. Kittel and A. H. Mitchell, Phys. Rev. **101**, 1611 (1956).
[29] A. Aharoni, *Introduction to the Theory of Ferromagnetism* (Oxford Science, New York, 2000), Chap. 3.5, pp. 48–59.