Magnetization reversal and two level fluctuations by spin-injection in a ferromagnetic metallic layer

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(Dated: November 4, 2018)

Slow magnetic relaxation and two level fluctuations measurements under high current injection is performed in single-contacted ferromagnetic nanostructures. The magnetic configurations of the samples are described by two metastable states of the uniform magnetization. The current-dependent effective energy barrier due to spin-transfer from the current to the magnetic layer is measured. The comparison between the results obtained with Ni nanowires of 6 μm length and 60 nm diameter, and Co (10 nm)/Cu (10 nm)/Co(30 nm) nanometric pillars of about 40 nm in diameter refined the characterization of this effect. It is shown that all observed features cannot be reduced to the action of a current dependent effective field. Instead, all measurements can be described in terms of an effective temperature, which depends on the current amplitude and direction. The system is then analogous to an unstable open system. The effect of current induced magnetization reversal is interpreted as the balance of spin injection between both interfaces of the ferromagnetic layer.

PACS numbers: 75.40.Gb, 75.60.Jk, 75.60.Lr

I. INTRODUCTION

The present paper adresses the problem of magnetization reversal provoked by injection of spin-polarized current (current-induced magnetization switching, or CIMS). In the context of the emergence of spintronics,[1] the discoveries of spin-injection,[2,3] giant-magnetoresistance,[4,5] and tunneling magnetoresistance[6] created an interest in playing with both the spin degree of freedom of the electrons and the usual electronic properties. The CIMS effect was first predicted[7,8] and observed recently by a series of measurements.[2,10,11,12,13,14,15,16,17,18,19,20,21] In these experimental works, the magnetization reversal is ascribed to the effect of the spin-polarized conduction electrons on the magnetization. Some microscopic mechanisms of spin transfer from the spin-polarized current to the magnetic layer have been proposed in the framework of different formalisms.[22,23,24,25,26,27,28]

Both experimental and theoretical approaches focus on the typical Co/Cu/Co pillar system, nanometric in all dimensions.[12,13,15,17,18,19,20,21] This is a pseudo spin-valve structure where the spacer Cu layer is about 10 nm and the Co layers vary from 1.5 to 30 nm. This structure is convenient because it is composed of a spin-polarizer of the current (“pinned” Co layer of 30 nm), and a magnetic layer which plays the role of an analyzer (“free” Co layer), so that the spin-polarization of the current is known. Furthermore, CIMS was associated with giant magnetoresistance (GMR), or spin accumulation, and used as a probe allowing magnetization configurations to be measured. The magnetic configuration of the two Co layers is either parallel or antiparallel. However, the CIMS effect was also measured on homogeneous Ni nanowires, with anisotropic magnetoresistance (AMR) as a probe, and without an explicit spin-polarizer.[22,23] The characteristics of CIMS in Ni nanowires and Co/Cu/Co pillars are very similar in all points,[22] except, in contrast to the pillar structure, it was not possible to reverse the magnetization in both directions at fixed field while inverting the sign of the current in the Ni nanowires. This last point could be attributed to the fact that the corresponding double well potential is too asymmetric to allow reversal in both directions. In this picture, the effect of the current is described in terms of effective temperature, but not as a current dependent effective field whose characteristic is to bias the profile of the energy potential.

In order to investigate this hypothesis, I discuss here the results of the experiments of the response of the magnetization to the current excitation. Experiments of slow relaxation are presented in terms of activation process out of a metastable state of the magnetization due to spin injection. The typical time range of the current excitation is about 0.1 to some tens of microseconds. At this time scale, the magnetization reversal (with or without current injection) is an instantaneous event because the typical time of the magnetization dynamics (the duration of the irreversible jump of the magnetization) is below the nanosecond.[22,23] A the time scale above some few nanoseconds, the dynamics is defined by the time needed to overcome the energy barrier due to Brownian motion.[24] Slow relaxation measurements (or after-effect measurements) and two level fluctuations hence allow to access to the energy barrier separating the two metastable states of the magnetization and to the profile of the energy potential. Slow relaxation measurements under current injection is consequently a direct measurement of the energy transferred from the current to the magnetic layer. Furthermore, we show that it is possible to differentiate between a transfer of energy due to the action of a (current-dependent) effective field or due to the action of a stochastic diffusion process or magnetiza-
tion exchange with spin-polarized reservoirs\cite{31}. In order to discuss the effect of precession and spin accumulation (or GMR), we present a comparative study between two different structures performed with an identical experimental protocol. Namely, electrodeposited Ni nanowires of 6 µm length and 60 nm diameter, and Co(10 nm)/Cu(10 nm)/Co(30 nm) pillar structures electrodeposited in the center of a Cu wire. The typical energy transferred of the first sample is about 30 000 K per mA (40 000 K in the center of a Cu wire). The typical energy transferred of the second sample is about 6 000 K per mA (2000 K for 10⁻² A/cm²) for the second sample.

II. SAMPLES

The samples are obtained by a template synthesis method applied to polycarbonate nanoporous membranes. The template synthesis method is described elsewhere\cite{16}. We start with a nanoporous membrane, e.g. a polycarbonate membrane, with a random lattice of parallel pores obtained by ion track technology. Such membranes are commercially available, with about 6 µm thickness and pore diameters down to about 30 nm. A metallic layer is deposited on the top (some few tens of nm in order to avoid blocking the pores) and the bottom (some few 100 of nm in order to block the pores). The membrane is then put into an electrolytic bath. The electrolytic deposition of the metals inside the pores forms the nanowires.

It is also possible to control the morphology during the growth by playing with pulsed electrolytic potentials in a bath with two or more ions. A structure of, e.g. one or more magnetic multilayer can then be deposited in the middle of a Cu wire\cite{15}. The potential between the two membranes is measured during the growth, in order to stop the deposition (with a feedback loop) as soon as a first contact is obtained. A single wire is then contacted to the top electrode during the growth. Using this method, I have studied the effect of current injection in the different structures shown in Fig. 1, from homogeneous 6 µm Ni nanowires\cite{10} to Co(30 nm)/Cu(10 nm)/Co(10 nm) nanopillars electrodeposited in the center of a Cu wire\cite{15}, via the hybrid structures composed of both a homogeneous Ni part and a multilayered Co/Cu part\cite{14}.

In these systems, the structure allows a current to flow perpendicular to the plane of the ferromagnetic layers (this is the so-called CPP geometry). Because the current is spin-polarized perpendicularly to the displacement of the electrons in the first ferromagnetic layer, the CPP geometry enables the spin injection with well-defined spin polarization in the next ferromagnetic layer. However, the spin accumulation, which describes the spin diffusion at the interface, smooth out the spin polarization in both sides of the interface\cite{2,3,32}. The spin diffusion length of electrodeposited Cu and Co is of the order of some few tens of nanometers. As will be described below, this spin-polarization allows the magnetization state to be observed with GMR measurements. However, beyond the GMR effect the spin injection may also lead to CIMS effect as evidenced by the magnetization reversal. In the case of homogeneous Ni nanowires, there is no explicit spin-polarizer, and no GMR can be measured. Instead, the magnetic configuration is measured by anisotropic magnetoresistance (AMR). However, also in this case CIMS effect can be observed, as shown below. The typical features discussed in this report have been reproduced in many samples of each kind, by varying the diameter and the length of the layers, and the resistance of the contacts.

III. SPIN-INJECTION INDUCED MAGNETIZATION REVERSAL

I shall try here to describe the observed effects from a phenomenological point of view of the measured magnetization reversal process, without introducing any hypothesis about the microscopic mechanism involved in the transport processes.

The first interest in working with magnetic nanostructures is to be able to measure a single magnetic domain. The typical size must hence be below the typical domain wall size, which is around 100 nm for Ni and 10 nm for Co. One can check experimentally that the samples are indeed single magnetic domain\cite{33} (if the magnetocrystalline anisotropy is weak, the stray field, or shape anisotropy field forbids the creation of domains perpendicular to the wire; this is the case in Ni samples (1) and (2) of Fig. 1, which is not the case in Co samples (3) of Fig. 1).
We manage furthermore, by selecting our samples, to have a uniaxial anisotropy in the Co layers. Under these assumptions the magnetic energy can be written in the following form:

\[ E = K \sin^2(\varphi) + M_S H \cos(\varphi - \theta) \]  \hspace{1cm} (1)

where \( K \) is the anisotropy constant (which includes shape anisotropy), \( \varphi \) and \( \theta \) are respectively the angle of the magnetization direction and the angle of the magnetic field \( H \) with respect to the anisotropy axis, and \( M_s \) is the magnetization at saturation. Note that \( H \) contains all components of the effective field (see below), except the anisotropy due to its quadratic dependence. This function displays a double-well potential as a function of the magnetic coordinate \( \varphi \) (Fig. 2).

The double well structure of the energy is the archetype of the hysteretic behavior. The critical field \( H_{sw} \) defined by a vanishing barrier height, describes an irreversible jump (and corresponds to the so-called spinodal limit). This corresponds to an irreversible switch of the magnetization from the position defined by the first energy minimum, to the other equilibrium position around \( \varphi = \pi \). This irreversible process occurs at \( H \approx H_{sw} \) in a time scale below one nanosecond.\(^{25,26}\) A change of the parameter \( H \) (at fixed \( \theta \)) with \( H \leq H_{sw} \) corresponds to a reversible rotation of the magnetization. A change in the parameter \( H \) with \( H_{sw} \leq H \) does not change the equilibrium position. The hysteresis is then composed by a reversible part and an irreversible part reduced to the magnetization reversal. The hysteresis is totally symmetric with respect the coordinate axes. The magnetic hysteresis loop for the Ni nanowire is measured through the anisotropic magnetoresistance (AMR) effect (Fig. 3(a)), at different angles \( \theta \). The typical amplitude of the AMR in Ni is about 2% of the resistance. In contrast, the hysteresis loop for the pillar structure is measured by the GMR effect (Fig. 3(b)) of amplitude 20 to 40% of the resistance of the active part of the sample (the Co/Cu/Co layers represent about 1% of the total resistance in sample (3) of Fig. 1). The reversible rotation of the magnetization is easy to see in the AMR response at large angle of the applied field (\( \theta \) about 80°) in Fig 3(c). The GMR of the pillar is measured with the applied field close to the anisotropy axis in the plane of the Co layers (\( \theta \) about 10°). The diameter of the Cu wire is now about 40 nm (37 ± 3), in order to maintain single domain behavior. The anisotropy is inside the plane of the layer, as shown by the minor loop plotted in Fig 3(d). The current injection is performed at fixed external field, at a given distance \( \Delta H \) to the irreversible switch \( H_{sw} \), and is represented in Fig. 3(c) and Fig. 3(d) by the arrows. The maximum distance \( \Delta H \) from the switching field with a current density of \( 10^7 \) A/cm\(^2\) is about 50 mT for the Ni nanowire (40% of the switching field) and 32 mT for the pillar structure (80% of the switching field).

\[ \frac{d\vec{M}}{dt} = g' M_s \left( \vec{M} \times \vec{H}_{eff} \right) + h' \left( \vec{M} \times \vec{H}_{eff} \right) \times \vec{M} \]  \hspace{1cm} (2)

where \( g' \) and \( h' \) are constant related to the gyromagnetic ratio and to the Gilbert damping coefficient. This
equation says that the variation of the magnetization is always perpendicular to the magnetization, whatever the effective field $\vec{H}_{\text{eff}}$, and is composed by a precessional term (including transverse relaxation), and a longitudinal relaxation (second term in the right hand side of the equation).

The equation (2) is deterministic. The effective field plays the role of a generalized force, thermodynamically conjugated to the Gibbs magnetic energy $E^{35}$.

$$\vec{H}_{\text{eff}} = -\nabla_M E$$ (3)

so that $\vec{H}_{\text{eff}}$ contains the anisotropy field $\vec{H}_a$, the applied field $\vec{H}_{ap}$, the dipole field $\vec{H}_d$ produced by the presence of the other layer (sample (3) of Fig. 1) if necessary : $\vec{H}_{\text{eff}} = \vec{H}_a + \vec{H} = \vec{H}_a + \vec{H}_{ap} + \vec{H}_{dip}$.

However, as far as we are working with nanostructures, the fluctuations are of fundamental importance, and a stochastic term must be added to the LLG equation. We obtain the (non-linear) rotational Langevin equation, or equivalently the rotational Fokker-Planck equation of the probability density $W$ which describes a rotational Brownian motion $^{35}$.

$$\frac{\partial W}{\partial t} = g' \vec{u} \cdot \left( \nabla_M W \times \vec{H}_{\text{eff}} \right) + h' \nabla_M \cdot (W \vec{H}_{\text{eff}}) + k' \nabla^2_M W$$ (4)

where the first term in the right hand size is the precessional term, the second term is the longitudinal relaxation, and the third term is the diffusion term. The constant $k'$ is evaluated by requiring that the Maxwell-Boltzmann distribution of orientations is the equilibrium solution of the energy minima. In order to analyze after-effect experiments (i.e. slow relaxation measurements), the activation process over the potential barrier is described with the relaxation time (or the first passage time) corresponding to an exponential relaxation. Since the precession occurs typically at some tens of picoseconds (1 to 100 picoseconds), as measured by ferromagnetic resonance, the precessional term is neglected $^{35}$ (this approximation will be discussed latter). The typical Néel-Brown law is then obtained:

$$\tau = \tau_0 \exp \left( \frac{E_0 (1 - H/H_{sw}^0)^\alpha}{kT} \right)$$ (5)

where $H_{sw}^0$ is of the order of the switching field at zero temperature, $\tau_0$ is the waiting time (10 ps to 1 ns) related to $k'$, $\alpha$ is very close to 1.5 for all angles $\theta$, except at zero and $\pi$ angles where it is equal to 2. The validity of this relaxation law has been tested on many magnetic nanostructures, including our electrodeposited Ni nanowires$^{35}$.

However, if the asymmetry of the double well potential is small with respect to the barrier height, the probability of jumping back to the initial state is important. The activation process is now described by the two relaxation times back and forth $^{35}$.

$$\begin{cases}
\tau_{up} = \tau_{0up} e^{(\Delta E_{down})/(kT)} \\
\tau_{down} = \tau_{0down} e^{(\Delta E_{up})/(kT)}
\end{cases}$$ (6)

where, $\tau_0$ is the waiting time related to the equilibrium position (local minima) for the parallel (up) and the antiparallel (down) magnetic configuration of the two Co layers. The presence of the two terms in Eq. (6) leads to expect a two level fluctuation (TLF) process during the measurements. The TLF process is less appreciated for device application, however it contains more information as the single irreversible jump, since both the barrier height and the asymmetry of the double well can be deduced.

What happens while injecting currents? The magnetic system composed by the magnetic layer must first be enlarged in order to take into account the magnetization of the current sources (i.e. some spin polarized reservoirs). The energy $\tilde{E}$ of this system is:

$$\tilde{E} = K \sin^2(\varphi) + M_S H \cos(\varphi - \theta) + \epsilon(I)$$ (7)

where $\epsilon(I)$ is the energy of the spin-dependent current source. A generalized effective field $\tilde{H}_{\text{eff}}$ is defined from the energy $\tilde{E}$ by the relation:

$$\tilde{H}_{\text{eff}} = -\nabla_M \tilde{E}$$ (8)

and this effective field contains an other term which includes the effect of the current : $\tilde{H}_{\text{eff}} = \tilde{H}_a + \tilde{H}_{ap} + \tilde{H}_{dip} + \tilde{H}(I)$. The exchange torque term $^{8}$ of the form $\vec{M} \times \tilde{H}(I)$ where $\tilde{H}(I) = Ia\langle s,M\rangle(\vec{s} \times \vec{M})$ and $\vec{s}$ is the spin polarization of the current must necessarily be completed by an other term to give $\tilde{H}_{\text{eff}}$, because it cannot be derived from a potential function. My goal is to present a phenomenological approach (based on the measured macroscopic magnetization $\tilde{M}$) and the link to microscopic approaches $^{7,8,22,23,24,25,26,27}$ is beyond the scope of the present work $^{35}$. Hence we write the generalized LLG equation, without any loss of generality, in the following form :

$$\frac{d\vec{M}}{dt} = g' M_s \left( \vec{M} \times \tilde{H}_{\text{eff}} \right) + h' \left( \vec{M} \times \tilde{H}_{\text{eff}} \right) \times \vec{M} + f(I,\tilde{M})\vec{M}$$ (9)

The third term in the right hand side of equation (9) is due to the so called longitudinal spin transfer which does not conserve the magnetization of the ferromagnetic
layer. \( f \) is a function of the current and the magnetization configuration. This terms includes all possible mechanisms which lead to non conservation of the magnetization, including generation of spin-waves or magnons due to the current or any relaxation channel from the spins of the conduction electrons to a ferromagnetic collective variable \( \dot{M} \). The other components of the spin-transfer (or Oersted fields) are included into the effective field.

In order to summarise, the usual Néel-Brown activation process (slow relaxation) allows one to access to the effective potential profile, and hence the current-dependent effective field. Since the third term added to the LLG equation and describes in (1) does not act on the potential profile, it is contained in the non-deterministic part of equation Eq. (1). The stochastic fluctuations hence include the thermal fluctuations \( kT \), the magnon generation, and any other relaxation channels from the spin-polarized current to magnetization. The corresponding energy (dashed parts in Fig. 2) defines the measured effective barrier heights \( \Delta E_{\text{eff}}^{\text{up}} \) and \( \Delta E_{\text{eff}}^{\text{down}} \). In the absence of a more detailed stochastic theory of activation due to spin transfer, it can conveniently be accounted for by a phenomenological effective temperature \( T_{\text{eff}}(I) \) such that \( E_{\text{eff}} = kT_{\text{eff}}(I) \). This temperature is expected to play a different role depending on the current sense, and is also expected to depend on the magnetic configuration.

In order to analyze the data presented below, let me first suppose that the third term in Eq. (1) is not present. This means that the system composed by the ferromagnetic layer is supposed to be closed (though non adiabatic due to the current injection), because the third term describes an open system. Then, the derivation of the activation process is unchanged, and we expect to measure the same relaxation process as described by equation (5) with \( H \) replaced by \( \tilde{H} \) (and \( \theta \) by \( \tilde{\theta} \)).

### IV. EXPERIMENTAL RESULTS

In this study, the response to the injection of current is measured at the time scale 0.1 to 10 microseconds. The time scale is chosen in order to avoid any non-stationary heating regimes. The measurements are performed using a Wheatstone bridge, and a Lecroy Gigasampler (the experimental set-up and the thermal regimes are discussed elsewhere). The external field is first set at saturation (± 1 Tesla), and then decreased to a fixed value \( H \). The current is injected with a step function at time \( t=0 \). The raising time of the current injection was changed between 0.01 to 1 microsecond (i.e. varying the cut-off frequency of the current excitation between 1 and 100 MHz) without significant change in the response of the magnetization. A statistical assessment is performed over many measurements, by cycling the hysteresis loop with the external field before each measurement. This protocol is repeated for different values of the applied field \( H_f \), and different values of the amplitude of the current excitation \( I \). The results are presented in Fig. 4 for the Ni sample (sample (1) of Fig 1) and Fig. 5 for the pillar sample (sample (3) of Fig 1).

**Ni nanowires.** Figure 4(a) shows the response of the resistance to the current excitation for a Ni nanowire. The first change in the voltage is due to the Joule effect, and a quasi-stationary regime is reached after about 1 microsecond, at a temperature of 390K. The small jump in the middle of the curve is the anisotropic magnetoresistance (AMR) response of the magnetization to the current injection. The jump is magnified in Fig. 4(b). Statistics of the switching time over many events allows one to get the exponential relaxation by integrating the histogram over the time. The mean relaxation time is then deduced, and plotted as a function of the external field for different currents in fig. 4(c). The fit of the curves are performed with the Néel-Brown activation laws Eq. (5), with the current dependence contained entirely in the energy term \( E_0 \). The curves of Fig. 4(c) cannot be accounted for by a current dependent field \( H(I)^{16} \). Instead, there is an energy variation as plotted in Fig. 4(d). If linearised (see e.g. the other sample reported in(25)) \( \Delta E_0 = a' I \), with \( a' = 30000 \text{ K/mA} \) (about 40 000 K/(10^7 A/cm^2)). Normalized to the anisotropy energy, the variation of the energy is about 30 % / mA. The energy of 30 000 K (2.10^-19 J) corresponds also to \( \Delta H_{\max} = 50 mT \) illustrated in Fig. 3(b).

**Pillar structure.** In order to insure single Co magnetic domain behavior, the pillar structure is electrodeposited in a wire of 37 nm ±3 nm in diameter, instead of 70 to 80 nm for the Ni nanowires. As a consequence, a current of 0.4 mA corresponds to about 10^7 A/cm^2. The same current density required an injection of about 1.5 mA in the Ni wire. The same protocol was applied to pillar structure (sample (3) of Fig. 1).
of the Co layer is about 400 times smaller than that of the Ni wire. The anisotropy energy is between 50 to 100 times smaller, depending on the crystallinity. The asymmetry of the double well is small with respect to the barrier height so that the probability of jumping back to the initial state is important. The activation process is now described by the two relaxation times back and forth described in Eq. (6). The TLF feature is indeed measured under current injection only, as shown in Fig. 5, for a large range of field and current. The TLF is observed over 0.1 T for the explored positive and negative currents. The amplitude of the jumps corresponds to the GMR signal (one Ohm) between the parallel and antiparallel magnetic configurations. The TLF behaviour was measured in other similar systems [12,13,17], and seems to be the main signature of the CIMS pseudo spin-values.

The TLF allows one to access two parameters, the mean time spent in the antiparallel configuration \( \tau_{\text{ap}} \) and the mean time spent in the parallel configuration \( \tau_{\text{down}} \). The ratio, plotted in Fig. 5(b) for positive currents gives the parameter \( \delta E(H) \), i.e. the variation of asymmetry of the energy profile. The value \( \ln(\tau_{\text{down}}/\tau_{\text{ap}}) = 1 \) corresponds to the symmetric double well. Note that different values \( \tau_{\text{ap}} \neq \tau_{\text{down}} \) should be expected but the difference is negligible with respect to the exponential behavior. More important is the possibility of different effective temperatures between both sides of the barrier, especially as a function of the current direction. This possibility, and its physical meaning, will be discussed in the next section. Under this last assumption, it can be seen that all happens as varying the current at fixed field were equivalent to bias the energy profile. The effect of the current would here be equivalent to the action of a field. Tuning the current can be exactly compensated by tuning the external field, in order to keep the energy profile unchanged (i.e. following an horizontal line in Fig. 5(b)). Except for pathological cases (the spinodal limit), keeping constant the energy profile means keeping constant the effective field \( \tilde{H}_{\text{eff}} \):

\[
E(\tilde{H}_{\text{eff}}) = \text{cst} \rightarrow \tilde{H}_{\text{ap}} + \tilde{H}_{\text{a}} + \tilde{H}_{\text{d}} + \tilde{H}(I) = \text{cst} \quad (10)
\]

This equation defines the function of the current \( H_{\text{ap}} = H_{\text{sym}}(I) \), plotted in Fig. 5(b) for a constant profile \( (\ln(\tau_{\text{down}}/\tau_{\text{ap}}) = 1) \) corresponding to the symmetric double well. The symmetric double well at zero current is located in the middle of the minor hysteresis loop (see [15]) for the external field \( H_{\text{sym}}(0) = -22 \text{ mT} \). The current dependent effective field is linear in current, \( H(I) = aI \), with a coefficient of the order of \( a = 0.1 \text{ T/mA} \) or 33 mT/(10\(^7\) A/cm\(^2\)). The coefficient \( a \) is of the same order of magnitude of what has been measured in previous studies in terms of critical currents \( I_c(H) \), where the Co layer (the analyzer) was 3 to 5 times smaller [12,13,17]. This analysis is based only on the existence of a current dependent effective field \( \tilde{H}_{\text{eff}} \). However, the TLF effect also gives access to the value of the energy barrier \( kT \cdot \ln(\tau_{\text{down}}(H_{\text{sym}})) = \Delta E_{\text{sym}}(I) \) as a function of the current for a fix energy profile (more precisely at a fixed ratio \( \tau_{\text{down}}/\tau_{\text{up}} \)) in Fig 5(c)). The result is plotted in Fig 5(c), for the symmetric double well profile. The variation as a function of the current amplitude is also very important and corresponds to 1000 K for a variation of 0.15 mA. The variation of the barrier height is approximately linear \( \Delta E_{\text{sym}}(I) = a'I \) with \( a' = 6800 \text{ K/mA} \) (more than 0.5 eV/mA) for positive current, and about 4000 K/mA for negative current (plotted in the inset of Fig. 5(c) and reported in [20]).

![FIG. 5: After-effect measurements measured on the Cu/Co/Cu pillar. (a) response of the voltage to the current injection of 0.4 mA (about 10\(^7\) A/cm\(^2\)). (b) Asymmetry of the double well \( \delta E \) as a function of the applied field for various current injections. (c) Values of the field as a function of the current for symmetric double well (defined by \( \delta E = 0 \)). (d) Variation of the barrier height \( \Delta E(H_{\text{sym}}) \) of the symmetric double well as a function of the current.](image)

![FIG. 6: Illustration of the two level fluctuation under current injection with the effect of the current described exclusively by the phenomenological effective temperatures \( T_{\text{eff}} \) and \( T_{\text{eff}} \) (see text). Potential profile for symmetric relaxation. From left to right: (a) profile of the potential for current injection +1 at \( H = -50 \text{ mT} \), (b) profile at \( H = -20 \text{ mT} \) without current injection, (c) profile at \( H = +15 \text{ mT} \) with current injection -1.](image)
The current dependence at fixed energy profile cannot be explained only with the current dependent effective field $\tilde{H}_{eff}$ defined in Eq. (4). Another mechanism is necessarily present. One possibility is the effect of the precession, i.e. a resonance, maintained in a stationary regime due to the current injection. The second possibility, which includes phenomenologically the first one (i.e. the precession) is to describe all features observed with the help of an effective temperature which depends on the current direction. In this picture, the horizontal dashed line $ln(\tau_{down}/\tau_{up}) = 1$ in Fig. 5(b) represents any double-well energy profile (i.e. $\delta E \neq 0$ if $I \neq 0$) but with equal effective energy barriers $\Delta E_{up}^{eff} = \Delta E_{down}^{eff}$ in the right and left wells. The effective temperatures $kT_{up}^{eff} \neq kT_{down}^{eff}$ are then different in both sides of the barrier. This means that the fluctuations (due either to the precession, or to the longitudinal spin transfer in Eq. (3)) are not equal in the right and left well, and depend on the current direction. This interpretation is depicted in Fig 6 together with some of the experimental data of the TLF measurements. Three different profiles of the double well are sketched corresponding to the symmetric effective barrier height. It can be seen that all data are accounted for within this picture. At fixed current injection, a line following the experimental points is due exclusively to the biasing of the energy profile provoked by the external field. In contrast, the variation of the amplitude or sign of the current injection is described in terms of effective temperature, or in terms of effective barrier heights.

The hysteresis loop with weak current and high currents of both directions is shown in Fig. 7. As already observed in a previous work, the hysteresis loop is enlarged for positive current and the hysteresis loop is shrunken for negative current. On the basis of the interpretation depicted above, the enlargement of the hysteresis loop for positive and the shrinkage of the hysteresis loop for negative current occurs if the energy $kT_{up}^{eff}$ or the energy $kT_{down}^{eff}$ is greater than the maximum barrier height (which corresponds to the symmetric double well). It follows that the state of the system is blocked in the opposite potential well by an effective barrier. For the antiparallel alignment, this process can be compensated by the Zeeman energy which is able to force the two Co layers to align at high enough magnetic field above the energy $kT_{eff}$ (at about 1 Tesla in our case). In the parallel configuration, the dipole field (which plays the role of the “exchange biasing” of real spin-valves) cannot be tuned, and there is no possibility for imposing the antiparallel configuration: the hysteresis disappears. This situation can be described as a directional superparamagnetism, where only one direction of the magnetization is averaged out, so that the other direction is imposed. Note that in this case, namely if $kT_{eff}$ is larger than the maximum energy barrier, the effect of the current injection is equivalent to adding magnetic momenta in a well-defined direction (instead of increasing the energy of the opposite magnetization state), and the description in terms of effective temperature (and the double well picture) is may not be longer relevant.

![FIG. 7: Half hysteresis loop for increasing field measured with 10 microseconds current pulses (no averaging). Continuous line: GMR reference hysteresis loop. Dashed: positive current at about 10$^7$ A/cm$^2$. Dots: negative current for the same amplitude.](image)

A. irreversible spin transfer

The variation of energy measured under current injection is about 40 000 K/(10$^7$ A/cm$^2$) (or 30 000 K/mA) for Ni nanowires and about 2000 K/(10$^7$ A/cm$^2$) (or 6600 K/mA) for pillar structures. More precisely, the results obtained about the activation process provoked by spin-injection show that a current-dependent effective field as defined in Eq. (4) and Eq. (5) is not sufficient to account for the two level fluctuation in Co/Cu/Co pillars and to the after-effect measurements in Ni nanowires. In contrast, all observed features can be interpreted phenomenologically without the need to invoke a current dependent effective field, but with a current dependent effective temperature.

How to interpret this effective temperature? One possibility is to store this energy in the form of precession of the magnetization described by the first term in Eq. (3). Under this hypothesis, the energies in the potential wells depicted in Fig 6 are simply the precession induced by the current (or any coherent spin-waves). Such a mechanism has been proposed by Berger in the term of SWASER (spin-wave amplification by stimulated emission of radiation) and is being studied by ferromagnetic resonance. Such precession, which would decrease the amplitude of the resistance jump from one state to the other has not been observed within the precision of our measurements (see raw data of Fig 4 (a) and 5 (a)), and this interpretation would hardly describe the effects observed on the hysteresis loop. Furthermore, if it is easy...
to understand that a high frequency excitation (beyond the GHz range) is able to maintain a ferromagnetic resonance (FMR) in a sample of arbitrary size, it is very hard, in contrast, to justify that a DC current, or a slow step function (with cut-off frequency below 100 MHz) is able to maintain a resonance over decades in a macroscopic dissipative system. The comparison between the two systems, Ni and Co/Cu/Co, with aspect ratio and size difference of more than a factor 100 (from about $10^6$ to $10^{10}$ coupled spins in the present study), shows that the effect do not originates from coherent spin-waves. However, the consequence of the spin transfer is of course, whatever its origin, a magnetic excitation which dissipates in the system in the form of magnetic switching, spin waves, solitons, or uses other more complicated dispersion channels.

The other possibility is that the effect is entirely described by the third term of Eq. (11) (the so called "longitudinal spin-transfer"). The system is then an open system and the variation of energy measured under current injection is transferred by the injection of magnetic moments at the interface. In the framework of this interpretation, it is necessary to imagine a relaxation process from the spin of the conduction electrons to the magnetization of the layer. Both objects are then supposed to be described by two separated sub-systems, like s and d electrons involving both spin channels (40, 41) (i.e. a four-channel model). This effect would be similar to that of a Light-emitting diode, with the difference due to the fact there is probably no well defined energy gap, and that the "emission-absorption" should be partially compensated between both interfaces in case of uniform magnetization.

Without entering in the details of a possible mechanism (see e.g. a thermokinetic approach of the four-channel approximation developed in reference(42) the energy involved may be of the order of the band splitting between the two up and down bands, i.e. of the order of 0.23 eV for Ni. Consequently, the energy of 30 000 K corresponds to a imbalance of a factor 10 in the efficiency of the spin injection between the top and the bottom of the wire or the two interfaces of the Co layer. At one interface, the relaxation of electrons from s to d of the minority spin channel leads to add magnetic momenta to the magnetic layer, and the effect is inverted at the other interface. If the two interfaces of the magnetic layer are perfectly symmetric, the spin injection is compensated at both interfaces. In contrary, if there is an asymmetry of the spin injection at both interfaces, a imbalance occurs and a net magnetization is injected in the layer. Consequently, CIMS effect should depend crucially on the symmetry of both interface. This prediction is corroborated by the measurements presented in Fig. 8, of a Ni nanowire with Ni contacts on one side (and Au on the other side), and Ni nanowire with Cu contacts (and Au on the other side). The wire with the Ni contact on one side shows a strong CIMS effect: the typical parameter is the slope $a=50$ mT/(10$^7$ A/cm$^2$). In contrast, the wires with Cu contacts have a negligible CIMS effect, whatever the size of the Ni wire (a set of samples from 5.5 microns down to 1 micron in length have been measured).

This interpretation is also corroborated by the counter-intuitive result that the amplitude of spin transfer is more important in homogeneous Ni than in GMR Co/Cu/Co pillars. This observation can be understood by the fact that spin-accumulation through the 10 nm thick Cu spacer layer in the pillar tends to smooth out the spin injection at both interfaces and tends to minimize the relaxation.

In conclusion, the measurements performed on the different electrodeposited samples show that the effect of the current cannot be reduced exclusively to the effect of a current dependent effective field (more precisely, an effective field thermodynamically defined as conjugated to the magnetization). If we assume that a macroscopic precession induced by a DC current during microseconds to seconds is not realistic, one is lead to conclude that the magnetic layer is an open system with respect to magnetic moments. This means that the spin-injection transfers magnetic moments from the current to the magnetic layer. The microscopic mechanisms responsible for this transfer, and the relation between the effective field defined here and the "exchange torque" introduced by Slonczewski and developed in many microscopic approaches, is still unclear in the absence of a stochastic theory of the magnetization reversal that includes spin transfer. However, the effect can be understood by assuming that the spin of the conduction electrons and the magnetization are two distinct quantities, so that some spins are able to relax from one system to the other, namely from the current to the ferromagnetic layer, leading to an important transfer in forms of magnetic moments. This relaxation can be mediated by magnon excitations, or other types of magnetic collective variables, but with typical relaxation time scales measured to be below 25 nanoseconds.

![FIG. 8: Variation of the switching field $\Delta H_{max}$ as a function of the amplitude of the current pulse. The sample with asymmetric interface (Ni contact) shows a strong $\Delta H_{max}$ while the sample with symmetric interface (Cu contact) has a negligible $\Delta H_{max}$.](image-url)
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