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Interpretation of relationship between current perpendicular to plane magnetoresistance and spin torque amplitude

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A simple interpretation of a number of experimental results is proposed concerning the linear relationship between the absolute current perpendicular to plane magnetoresistance amplitude and the spin torque amplitude (assumed to be inversely proportional to the critical current for current-incuced switching) observed in several series of spin-valve structures. The model is based on the assumption that the spin torque prefactor is proportional to the total transverse current polarization which is itself proportional to the longitudinal polarization of the current due to the pinned layer only. The latter is calculated by using the semiclassical theory of current perpendicular to plane giant magnetoresistance (Valet and Fert theory) when switching off the bulk and interfacial scattering asymmetry in the free layer.

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I. INTRODUCTION

The discovery of giant magnetoresistance[1] (GMR) in magnetic multilayers (MML) has opened a very active field of research and development nowadays called spin electronics, with important applications such as read heads[2] and nonvolatile memories.[3] Initially, GMR was discovered and studied in current-in-plane (CIP) geometry. However, the current perpendicular to plane (CPP) geometry rapidly received attention[4] because it potentially offers larger GMR amplitude than the CIP geometry and allows a more direct determination of the relative contribution of bulk and interfacial spin-dependent scattering. The CPP-GMR was first interpreted within a two-channel serial resistance network. This model was proven to be valid only when spin-flip is negligible, which is almost never the case in practical situations. Valet and Fert[5] (VF) then proposed a more detailed theory of CPP-GMR which takes into account spin-flip and underlines the importance of spin relaxation and spin accumulation effects in the transport perpendicular to the interfaces in magnetic materials. All these magnetoresistive effects allow modifying the electrical resistance of a magnetic multilayer (i.e., the way the current of conduction electrons flows in the structure) with the control of the orientation of the magnetization in the various layers of the multilayered stack. A few years later, the reciprocal effect was independently predicted by Slonczewski[6] and Berger:[7] when a spin-polarized current traverses a magnetic layer with a spin polarization at an angle with the local magnetization, the spin of the incoming electrons is very quickly reoriented parallel to the local magnetization, thus leading to a transfer of angular momentum. The latter is equivalent to a torque [spin-transfer torque (STT)] acting on the magnetization of the magnetic layer. This torque may lead to various effects such as current-induced magnetization switching or generation of steady magnetic excitations. The prediction of the spin-transfer torque has stimulated several successful experiments.[8–12] In particular, the observation of current induced switching in Co/Cu/Co nanopillars has attracted considerable interest[9] because of the possibility to use this phenomenon as a new way to write information in magnetic materials. From a theoretical point of view, this phenomenon also received considerable attention. Two main classes of theories can be distinguished: a first category treats the spin current as a ballistic current and ascribes the spin torque to the absorption of the transverse component of the spin current entering in the magnetic layer.[6] This absorption takes place within a very short distance of the order of 1 nm[13] from the interface between the nonmagnetic spacer and the magnetic layer as represented in Fig. 1. The second class of theories treats the transport in the diffusive limit. The emphasis is then put on the transverse spin accumulation at the nonmagnetic spacer/free layer interface.[10,14,15] The discontinuity of the transverse spin accumulation at this interface is equivalent to an "amplified" transverse spin current which yields the spin-transfer torque. Despite this significant theoretical effort,[13–19] the physics of this phenomenon is not yet fully understood.

We propose here a model establishing a simple relationship between STT amplitude [defined as the prefactor $G_{P(AP)}$ intensity—see, e.g., Eq. (1)] and absolute CPP-GMR (defined as the product between the sample area and the difference between resistances in antiparallel state and parallel state). On one hand, it is based on the theoretical ballistic

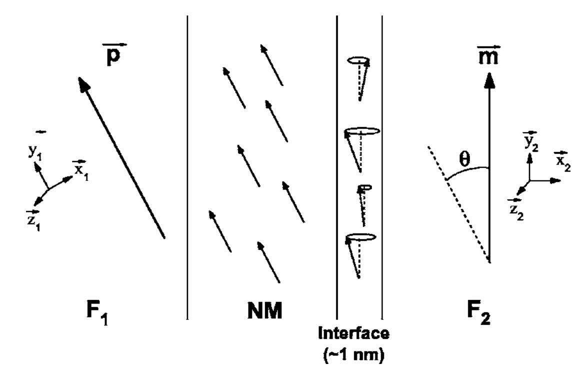

FIG. 1. Spin transfer in a trilayer structure. The current flows from right to left (i.e., electrons flow from left to right).

model of STT but on the other hand, it also uses the diffusive approach to calculate the current polarization which generates the STT in a magnetic multilayered structure. After introducing the modified Landau-Lifshitz-Gilbert equation of motion (Sec. II A) and the notion of transverse current polarization (Sec. II B), we introduce in Sec. II C the basis of our model which consists of estimating the STT amplitude from the evaluation of the longitudinal current polarization due to the pinned layer only at the location of the free layer in CPP spin valves.[20] In Sec. II D, we present a very simple resistance network approach which provides a simple understanding of the relationship between the three quantities: STT, absolute CPP-GMR amplitude, and current polarization due to the pinned layer in a spin-valve structure. Sections III to VII propose some interpretations of different experimental results in the framework of this model. We conclude this paper in Sec. VIII with a reminding of the main features and the limits of this model.

II. PHENOMENOLOGICAL MODEL

A. Introduction to modified Landau-Lifshitz-Gilbert equation

In a ballistic framework, considering a trilayer composed of two ferromagnetic (FM) electrodes F_1 (pinned layer) and F_2 (free layer) separated by a nonmagnetic spacer (NM), Slonczewski[6] showed that the Landau-Lifshitz-Gilbert (LLG) equation of magnetization dynamics is modified by a STT term which becomes important when an electrical current is injected into the MML structure. The LLG equation is then written:

$$\frac{d\vec{m}}{dt} = - \gamma\vec{m} \times \overrightarrow{H_{eff}} + \alpha\vec{m} \times \frac{d\vec{m}}{dt} - G_{P(AP)}J\vec{m} \times (\vec{m} \times \vec{p}), \tag{1}$$

where γ is the gyromagnetic ratio, α the Gilbert damping coefficient, J is the current density, $G_{P(AP)}$ is the coefficient of the STT term depending on the orientation of the FM layers (P: parallel configuration, AP: antiparallel configuration) and $\overrightarrow{H_{eff}}=\overrightarrow{H_{appl}}\pm\overrightarrow{H_{an}}-\overrightarrow{H_d}$, where the right-hand terms are, respectively, the applied field, the anisotropy field, and the demagnetizing field (+ or − depending on the P or AP configuration). It is interesting to note that some theoretical publications found a similar expression of the LLG equation using a different approach.[21]

The most largely accepted theory (see Ref. 13 for example) of STT in a MML type spin valve explains the torque by the absorption of the transverse component of the spin current flowing from the pinned layer to the free layer, and thus its transfer to the background magnetization of the free layer, within the NM/F_2 layer interface. This absorption is due to incoherent precessions of the spins across the NM/F_2 interface, which cancels (and transfers by angular momentum conservation) the spin current transverse component—see for example Fig. 1.

B. Transverse current polarization

Recently, several research groups have shown a correlation between absolute CPP-GMR amplitude and STT efficiency, when changing one parameter (for instance replacing an increasing fraction of Cu by CuPt in the spacer layer[22]) in various series of spin-valve structures.[22,23] This correlation showed up as a linear relationship between the inverse of the critical current required for switching the magnetization of the free layer and the absolute CPP-GMR amplitude. Our model is based on the assumption that the spin torque prefactor is proportional to the total transverse current polarization which is itself proportional to the longitudinal polarization of the current due to the pinned layer alone. This picture was first proposed in Ref. 22 and is developed here after.

The justification of this picture comes from an approximate superposition principle that we propose which states that the current polarization at a given point of the structure is the sum of the current polarization due to the pinned layer F_1 only (assuming that the free layer is nonmagnetic, i.e., assuming zero interfacial and bulk scattering asymmetry in this layer) and of the current polarization due to the free layer F_2 only (assuming that the pinned layer is nonmagnetic). Thus, the total current polarization at any point in the structure $\overrightarrow{P_{Total}}$, can be written as the contribution of the current polarization due to the pinned layer $\vec{P}_1$, and the current polarization due to the free layer $\vec{P}_2$:

$$\overrightarrow{P_{Total}} = \vec{P}_1 + \vec{P}_2. \tag{2}$$

To probe this superposition assumption, we compared the calculated longitudinal polarization in a typical multilayered spin valve of composition Cu(10 nm)/Co(8 nm)/Cu(6 nm)/Co(2 nm)/Cu(10 nm) due to both electrodes to the sum of the independently calculated polarizations due to free layer only and to pinned layer only. The calculations are perform using a code based on Valet and Fert theory.[24] Results are shown in Fig. 2 for the P [Fig. 2(a)] and AP [Fig. 2(b)] configuration. For the P configuration the difference between the global polarization and the summed polarization is about 4%, whereas for the AP configuration it is less than 2%. This confirms that the superposition assumption although not exact is a relatively good assumption in these structures. We can then use this superposition principle to estimate the transverse polarization which is the key parameter in determining STT amplitude.

Obviously, the polarization of the spin current due to the free layer is strictly parallel to the background magnetization of this layer. Therefore the transverse component is only due to the pinned layer. The transverse polarization flowing in the free layer, due to the pinned layer, can be calculated (see Fig. 1) from the longitudinal polarization due to the pinned layer:

$$\vec{P}_1 = \vec{P}_1^t + \vec{P}_1^l \tag{3}$$

$$P_1^t = \sin(\theta)P_1^l, \tag{4}$$

where θ is the angle between the magnetization of the free and pinned layers, P_1^t and P_1^l are, respectively, the transverse and the longitudinal components of the current polarization due to the pinned layer at the location of the free layer.

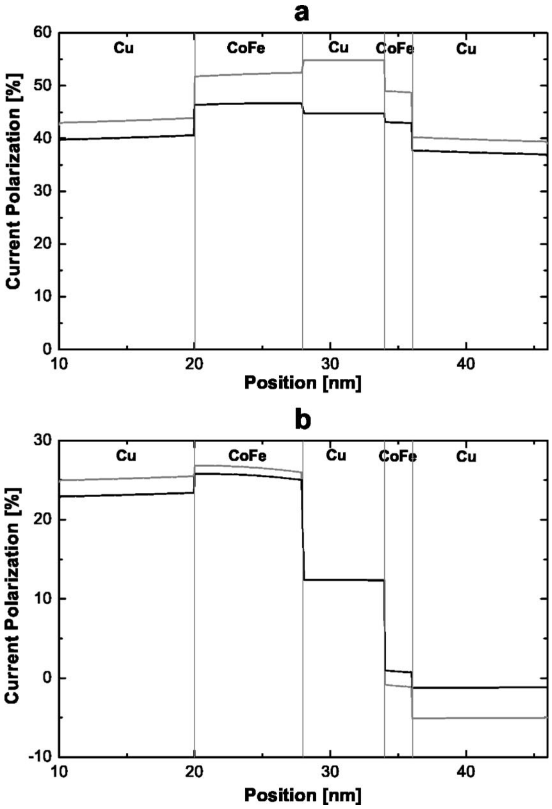

FIG. 2. Comparison between calculated current polarization due to both pinned and free layer (black) and the sum of both current polarizations calculated independently (grey) in P [Fig. 2(a)] and AP [Fig. 2(b)] configuration.

The longitudinal component of the current polarization due to the pinned layer is calculated by using the code presented above.[24] This code allows us to calculate the current polarization, spin accumulation, and resistance in arbitrary MML structures taking into account all CPP parameters used in VF theory such as bulk resistivity (ρ), spin diffusion length (l_{sf}), bulk spin asymmetry (β), interfacial spin asymmetry (γ), interfacial resistance (r), and interfacial spin flip (δ). In this calculation, the bulk and interfacial scattering asymmetries in the free layer are set to zero so as to isolate the contribution to the polarization of the current due to the pinned layer only.

C. Relationship between STT and transverse current polarization

Let us consider the previous simple trilayer F_1(pinned)/NM/F_2(free). Using the formula of Grollier *et al.*,[25] the STT amplitude in Eq. (1) can be written:

$$G_{P(AP)} = \frac{2\mu_B P_{transverse}^{P(AP)}}{tM_s e}, \tag{5}$$

where $P_{transverse}^{P(AP)}$ is the polarization of the transverse spin current flowing from F_1 into F_2, near the parallel (P) and antiparallel (AP) configuration, M_s is the free layer magnetization, and t its thickness (μ_B is the Bohr magneton and e the positive electrical charge). Following this, the expression of the switching current can be derived (i.e., the threshold current at which the free layer magnetization switches from the P to AP or AP to P configuration depending on its direction):

$$J_c^{P(AP)\rightarrow AP(P)} = \mp \frac{\alpha\gamma}{G_{P(AP)}}\left(\pm H_{appl} + H_{an} + \frac{H_d}{2}\right). \tag{6}$$

One can establish the following correlation:

$$G_{P(AP)} \propto \frac{1}{J_c^{P(AP)\rightarrow AP(P)}} \propto P_1^t \propto P_1^l. \tag{7}$$

Therefore, the more polarized the longitudinal spin current, the larger the STT amplitude.

D. Relationship between CPP-GMR and polarization

In order to get a simple image of the relationship between absolute CPP-GMR and current polarization due to pinned layer, a very simple two-channel model can be used as exposed in the introduction, neglecting interfacial effects. Considering that the resistivity of the NM layer is weak compared to the resistivity of the FM layer, we find the well-known formula:

$$A\Delta R = \frac{(\rho_1^{\uparrow} + \rho_1^{\downarrow})(\rho_2^{\uparrow} + \rho_2^{\downarrow})}{(\rho_1^{\uparrow} + \rho_1^{\downarrow})/t_2 + (\rho_2^{\uparrow} + \rho_2^{\downarrow})/t_1} P_1 P_2, \tag{8}$$

where $\rho_i^{\uparrow(\downarrow)}$ is the spin-dependent resistivity of FM_i for up spins (respectively, down spins), t_i is the thickness of FM_i, A the area of the sample, and P_i is the polarization of the spin current due to the FM layer i. The prefactors $\rho_i^{\uparrow} + \rho_i^{\downarrow}$ are not spin dependent. We note also that in this model, the polarization of one ferromagnetic layer P_i has the same definition as the bulk spin asymmetry β introduced previously in the VF model.

However, we point out that Eq. (8) is only valid within very stringent conditions: resistance of the stack dominated by the two ferromagnetic layers and no spin flip in the stack. This is why the absolute CPP-GMR will be calculated using the code presented above which takes into account every layers contributions and spin-relaxation effects.

We chose to calculate $A\Delta R$, the absolute magnetoresistance, instead of $\Delta R/R$ the relative magnetoresistance because the former is more directly related to the intrinsic value of the CPP-GMR in MML structure. Thus, one can establish a simple relationship between the longitudinal component of the spin current and the STT amplitude on the one hand, and the longitudinal spin polarization and the CPP-GMR on the other hand. Hence, within this very simple model, a linear dependence of the STT amplitude on the CPP-GMR can be written:

$$G_{P(AP)} \propto \frac{1}{J_c^{P(AP)\rightarrow AP(P)}} \propto A\Delta R. \tag{9}$$

We will now use this approach to interpret four recent experimental results.

TABLE I. CPP parameters used in calculations. The top table gives bulk values whereas the bottom one gives interfacial values.

	Bulk resistivity $\rho[\mu\Omega\ \mathrm{cm}]$	Bulk asymmetry β	Spin diffusion length l_{sf}[nm]
Co	15	0.35	38
Cu	2	0	100
Ru	20	0	14
$Co_{90}Fe_{10}$	20	0.7	25
$Ni_{84}Fe_{16}$	20	0.6	4.5
$Cu_{94}Pt_6$	35	0	7
	Interfacial resistance $r[\mathrm{m}\Omega\ \mu\mathrm{m}^2]$	Interfacial spin asymmetry γ	Interfacial spin memory loss δ
Co/Cu	45	0.7	25%
Co/Ru	48	−0.2	
$Co_{90}Fe_{10}$/Cu	45	0.75	25%
$Co_{90}Fe_{10}$/Ru	48	−0.2	31%
Cu/Ru	48	0	35%
$Ni_{50}Fe_{50}$/Cu	25	0.63	33%

III. CPP-GMR AND STT IN SIMPLE AND SYNTHETIC PINNED LAYER

In a first experiment, Emley *et al.*,[26] compared two MML structures composed of Co_{pinned} (8 nm)/Cu(6 nm)/Co_{free} (2 nm) (sample A) and Co_{bottom} (11.5 nm) /Ru (0.7 nm)/Co_{pinned} (8 nm)/Cu (6 nm) /Co_{free}(2 nm) (sample B). Sample A is a classical CPP spin valve used in STT experiments whereas sample B comprises a synthetic pinned layer, in which a Ru layer induces a strong antiferromagnetic (AFM) coupling between two Co layers. This AFM coupling increases the pinning of the Co reference layer and minimizes the overall dipolar stray field from the synthetic pinned layer on the Co free layer. The authors observed a decrease of the absolute magnetoresistance area product $A\Delta R$, by a factor of 2.1: $(A\Delta R)_A = 0.94 \pm 0.19\ \mathrm{m}\Omega\ \mu\mathrm{m}^2$ and $(A\Delta R)_B = 0.45 \pm 0.07\ \mathrm{m}\Omega\ \mu\mathrm{m}^2$.

We can explain this result in terms of spin-memory loss at the Ru/Co interfaces and use these experimental data to quantitatively determine the spin memory loss coefficient at this interface by using the CPP calculation code presented above.[24] All other CPP parameters that we used are taken from the literature and listed in Table I.

The interfacial spin memory loss (or interfacial spin flip) induces a discontinuity in the spin current. This loss of spin memory in such a narrow region is given by the parameter of interfacial spin flip δ, which is the percentage of polarization loss at the interface. To introduce the interfacial spin flip, we artificially replace the interface by an interfacial layer of thickness t_{int} having a bulk resistivity ρ_{int} such that $\rho_{int} \cdot t_{int} = RA$ and a bulk scattering asymmetry (β_{int}) corresponding to the actual interfacial asymmetry and characterized by a spin flip diffusion length such that $l_{sf}/t_{int} = 1/\ln[1/(1-\delta)]$. For example, a Co/Cu interface is modeled by a 1 nm-thick layer, with an effective bulk resistivity $\rho_{\mathrm{Co/Cu}}$ leading an interfacial RA product ρt of 0.45 $\mathrm{m}\Omega\ \mu\mathrm{m}^2$, an effective bulk spin asymmetry of 0.7, and an effective spin diffusion length $l_{sf}/1\ \mathrm{nm} = 1/\ln[1/(1-0.25)] = 3.47$.

With these values, we calculate an absolute MR area product of $A\Delta R = 0.955\ \mathrm{m}\Omega\ \mu\mathrm{m}^2$ for sample A which is quite close to the experimental value. Then, by calculating the dependence of the absolute magnetoresistance on the spin flip coefficient at the Co/Ru interface all other parameters being fixed, as shown in Fig. 3, and comparing the calculation with the experimental results, a spin flip coefficient of 26% can be derived for $A\Delta R = 0.456\ \mathrm{m}\Omega\ \mu\mathrm{m}^2$ in sample B. We also present in Fig. 4 two plots of the longitudinal polarization of the spin current due to the pinned FM layer in both cases. As already pointed out, in these calculations, we artificially set to zero the effective spin asymmetry of the free layer (β and γ), in order to calculate the longitudinal polarization (proportional to transverse polarization) due to the pinned layer only. We find that the current polarization in the free layer in sample B is 2.2 times weaker than in sample A. The synthetic AFM layer significantly reduces the spin current polar-

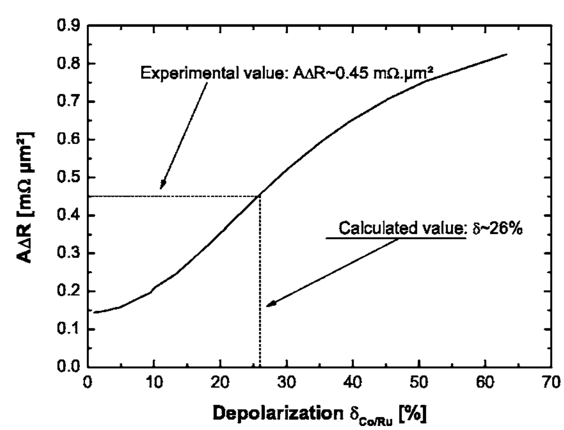

FIG. 3. Calculated absolute MR in sample A vs Co/Ru interfacial spin flip coefficient.

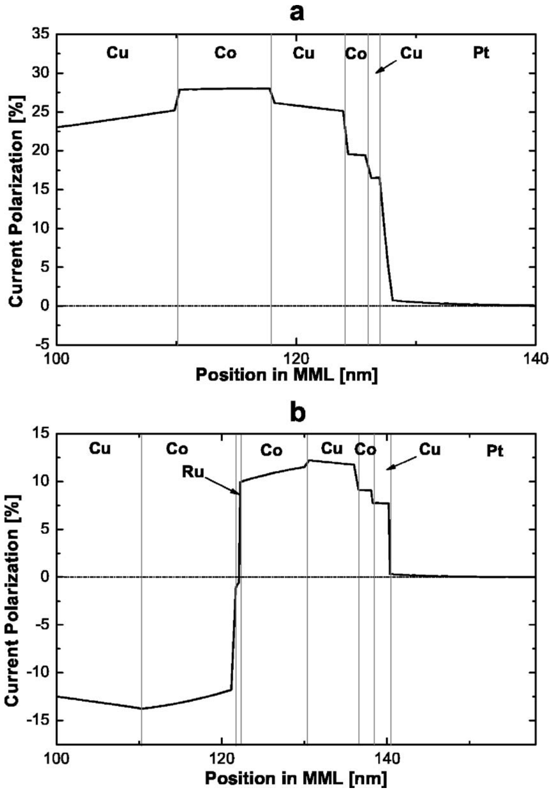

FIG. 4. Calculated current polarization due to the pinned layer in sample A (a) and sample B (b).

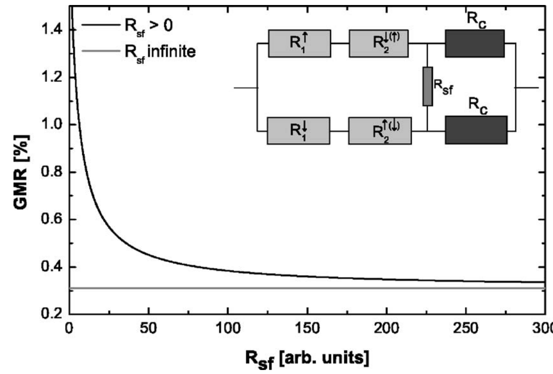

FIG. 5. Calculated CPP-GMR in a resistor model taking into account the spin flip between the free electrode and the contact resistance. The contact resistance is set at Rc=15 *r*.

ization because of the opposite role of the two antiparallel layers constituting the synthetic AFM in generating the current polarization and due to the negative scattering asymmetry at Co/Ru interface. However, thanks to the interfacial spin flip at the Co/Ru interfaces, the detrimental effect of the outer pinned layer is significantly reduced so that a still significant current polarization can be obtained even with a synthetic AFM.

We now compare this reduction of the current polarization due to the pinned layer at the location of the free layer with the experimental critical current densities for current induced switching determined by Emley *et al.*

To achieve STT, the authors needed a strong pinning of the fixed layer in sample A. To do so, instead of using an 8 nm-thick fixed layer of Co, they used a 40 nm-thick layer. We could verify that this difference of thickness weakly influences the current polarization due to the pinned layer (the absolute MR is of $A\Delta R = 1.09\ \mathrm{m}\Omega\ \mu\mathrm{m}^2$ compared with $A\Delta R = 0.955\ \mathrm{m}\Omega\ \mu\mathrm{m}^2$). Thus we can compare the absolute MR measurements with the inverse switching currents. Emley *et al.* found

$$(J_c^{P\to AP} - J_c^{AP\to P})/t = 3 \pm 1 \times 10^7 A/(\mathrm{cm}^2\mathrm{nm}) \text{ in sample A}, \quad (10)$$

$$(J_c^{P\to AP} - J_c^{AP\to P})/t = 7 \pm 1 \times 10^7 A/(\mathrm{cm}^2\mathrm{nm}) \text{ in sample B}, \quad (11)$$

t is the thickness of the free Co layer. From these measurements, the authors found a ratio between inverse switching currents of 2.3. This is in good agreement with the ratio of calculated polarization 2.2 and ratio of calculated absolute MR 2.4 in samples A and B.

IV. INTERPRETATION OF GMR AND STT WITH RU CAPPING

Another publication of Jiang *et al.*[23] used a MML spin valve composed of Cu(20 nm)/IrMn(10 nm) /$Co_{90}Fe_{10}$ (5 nm)/Cu (5 nm)/$Co_{90}Fe_{10}$ (2.5 nm)/Ru (t nm) /Cu(5 nm)/Ta(2 nm) and studied the influence of the Ru capping layer. They observed that adding a thin Ru layer (t =0.45 nm) reduces the critical current for magnetization switching, and thus increases the STT amplitude. Correlatively, an increase in the CPP-GMR due to the Ru capping was also observed by the same authors.[27] They ascribed this effect to a strong scattering of the majority electrons due to Ru/CoFe negative interfacial spin asymmetry ($\gamma \approx -0.2$). But this contribution has a negative impact on the CPP-GMR; we believe this phenomenon is not at the origin of the larger STT efficiency. We can explain these experimental results considering the spin flip due to CoFe/Ru interface. Calculating the resistance area product of the MML structure, we find $RA \approx 0.025\ \Omega\ \mu\mathrm{m}^2$, whereas the authors show a RA product of $\approx 0.23\ \Omega\ \mu\mathrm{m}^2$. We deduce that these samples exhibit a quite large contact resistance of $\approx 0.2\ \Omega\ \mu\mathrm{m}^2$ which represents about 90% of the pillar resistance.

As a first step, to understand the beneficial effect of spin flip between the active part of the spin valve (i.e., pinned layer/spacer/free layer) and the outer electrode, let us consider a simple resistor model, in the inset of Fig. 5, where R_{sf} is the equivalent spin-flip resistance linking up-spin and down-spin channels. Within the two spin-channel model, this simple network represents the two magnetic layers constituting the active part of the spin valve in series with the contact resistance. No spin flip is assumed except at the interface between the active part of the spin valve and the contact resistance where the spin flip resistance R_{sf} was introduced. The smaller this resistance, the stronger the spin mixing. By calculating the equivalent resistance of this system, we find that CPP-GMR is enhanced by adding this spin-mixing resistance and is always higher than with infinite R_{sf} (no spin

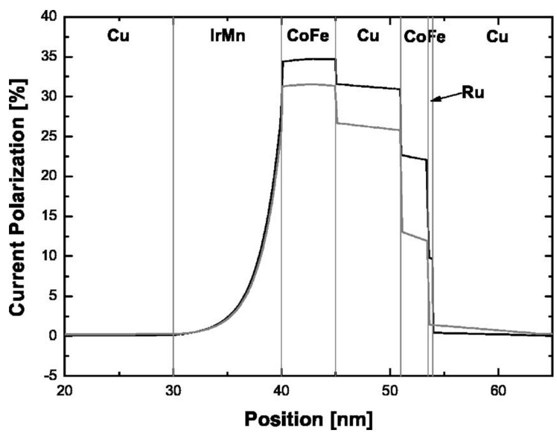

FIG. 6. Calculation of current polarization due to pinned layer in spin-valve structure with (black) and without (grey) Ru capping.

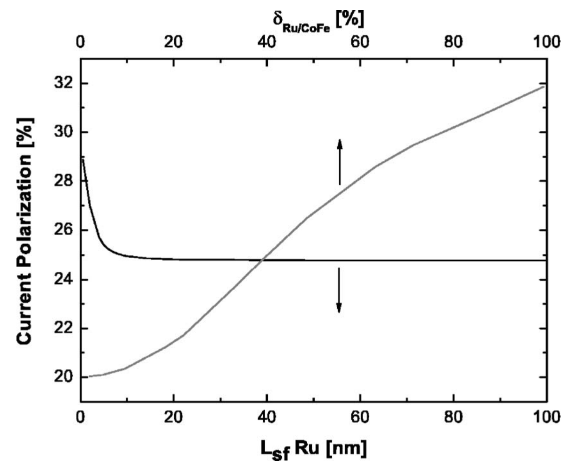

FIG. 7. Variation of the current polarization vs spin-diffusion length of Ru layer (black) where interfacial spin-flip is taken at 31%; Variation of the current polarization vs Ru/CoFe interfacial spin flip (grey), where spin-diffusion length of Ru is taken at 14 nm.

flip). This simple result means that spin flip allows the equalization of current in both channels, up and down, in the contact resistance R_c. This effect was already pointed out by the Michigan State University group.[22] They inserted a 1 nm-thick $Pt_{50}Mn_{50}$ layer on the top of the active part of a CPP spin valve (i.e., between the free layer and the top electrode) and they observed an increase of the absolute magnetoresistance and a decrease of the critical currents. They attributed this effect to the very short spin diffusion length of the PtMn layer (2 nm) which helps the polarization to quickly vary between the active part of the spin valve where the current polarization should be as large as possible and the nonmagnetic electrodes where the polarization should be zero. Hence, the insertion of a strong spin scatterer between the active part and the outer part of a spin valve, which was known to increase the CPP-GMR, also seems to increase the STT amplitude. To test this idea in a more accurate way, we calculated once again the polarization of the spin current due to the pinned layer in both cases (with and without Ru capping). The parameters are set in Table I and the results are shown in Fig. 6; the polarization of the longitudinal component of spin current polarized by the pinned layer is enhanced thanks to the strong interfacial spin flip of the Ru/CoFe interface as shown in Fig. 7. In this figure, the influence of both spin-diffusion length and interfacial spin flip on polarization is shown. It is clear that the main impact comes from the interfacial spin flip (31% for Ru/CoFe interface) rather than from the spin diffusion length of Ru which is not short enough (14 nm) to really enhance the current polarization. However, we find that the polarization is only enhanced by a factor of 2 whereas the authors find an increase of the STT amplitude of roughly 8. Considering the apparently large contact resistance of the samples, other factors related to the process fluctuations in the nanostructuring of the pillar may contribute to this large experimental factor. Nevertheless the trend obtained with our calculation is in agreement with the experimental result.

Therefore we have shown in the analysis of the previous experiments, that a strong spin memory loss of 30% takes place at CoFe/Ru interface. This interfacial spin flip increases the ability for the spin current to get polarized or depolarized, depending on the local spin scattering asymmetry. Considering there is a quite large contact resistance (this is commonly the case in patterned samples), this strong spin flip allows the current polarization to build up between the outer electrode and the active part of the spin valve.

V. LINEAR RELATIONSHIP WITH STRONG SPIN SCATTERER INTRODUCED IN THE SPACER

A third experiment was carried out by Urazhdin *et al.*[22] They studied the relationship between CPP-GMR and switching current using a MML structure composed of Cu(80 nm)/Py(30 nm)/Cu(13.5–*d* nm)/$Cu_{94}Pt_6$(*d* nm)/Cu(1.5 nm)/Py(6 nm)/Cu(2 nm)/Au(150 nm) (Py is Permalloy, i.e., $Ni_{84}Fe_{16}$). CuPt has a short spin diffusion length, as measured by Park *et al.*[28] and Yang *et al.*[29] It has also been shown that interfacial spin flip in Cu/Pt structures is very high[31] (90–99% at low temperature). By fitting the experimental dependence of the absolute CPP-GMR on the spacer thickness (Fig. 8) measured by Urazhdin *et al.*, we found a spin diffusion length of 7 nm in agreement with Refs. 28 and 29.

Varying the thickness of the CuPt layer in the sample, the authors found a linear relationship between absolute CPP-GMR and the inverse of the switching current. We calculated in the same structure the correlation between polarization and CPP-GMR and we found in Fig. 9 a linear relationship in agreement with the experiment. As explained at the beginning of this article, the switching current is inversely proportional to the STT amplitude, and so, to the absolute CPP-GMR.

VI. NEGATIVE SPIN ASYMMETRY

Finally, this interpretation is in good agreement with the results published by AlHajDarwish *et al.*[30] Using Fe(Cr) and Ni(Cr) alloys as FM electrodes, they studied spin valves with positively or negatively polarized electrodes. In a negatively

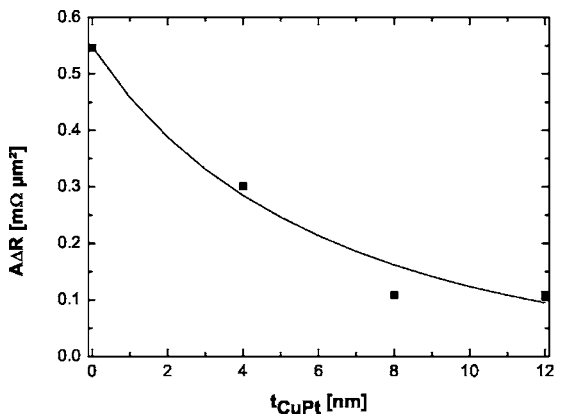

FIG. 8. Calculated fit (black line) of experimental measurements (squares) of the dependence of the absolute MR on the thickness of CuPt spacer layer. The CPP parameters taken for the calculation are shown in Table I. We find CuPt spin-diffusion length of 7 nm.

polarized electrode, majority spins are more scattered than minority spins; especially, in the Fe(Cr) layer, both bulk and interfacial spin asymmetries are negative,[30,32] and in the Ni(Cr) FM layer, only the interfacial spin asymmetry is negative.[30] In a MML spin-valve, when both electrodes are negatively polarized, they found a normal CPP-GMR (lower resistance for parallel configuration) and an inverse STT effect (current induced magnetization switching occurs at an opposite switching current compared to a sample where both electrodes are positively polarized). Moreover, when the electrode's polarizations are different, the CPP-GMR is always negative (higher resistance in a parallel configuration) and the STT depends on the polarization of the pinned FM layer (normal STT if positively polarized and inverse if negatively polarized).

We have here another confirmation of the key role of the pinned FM layer in STT. Furthermore, if the sign of the CPP-GMR depends on the relative sign of the spin asymmetry of each electrode, the STT amplitude can be reversed only by reversing the pinned layer effective spin asymmetry. In Fig. 10, we calculated the current polarization in a Fe(Cr)/Cr/Fe(Cr) structure, varying the bulk spin asymmetry of the pinned FM layer, conserving the interfacial spin asymmetry negative. We find that due to the negative interfacial spin asymmetry, the CPP-GMR remains negative and the current polarization due to the pinned layer is positive for $\beta \geq 0.027$ (spin scattering is dominated by bulk spin asymmetry); and inversely, absolute CPP-GMR is positive and current polarization negative when $\beta \leq 0.027$ (spin scattering is dominated by interfacial spin asymmetry). In AlHajDarwish *et al.* experiments, Fe(Cr) having a negative bulk spin asymmetry (see Table I), the authors find a reversed STT amplitude and a normal MR, as can be see in Fig. 10.

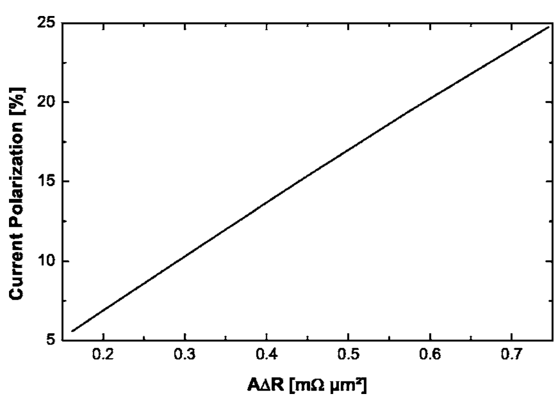

FIG. 9. Calculation of current polarization due to pinned layer vs CPP-GMR, varying CuPt layer thickness.

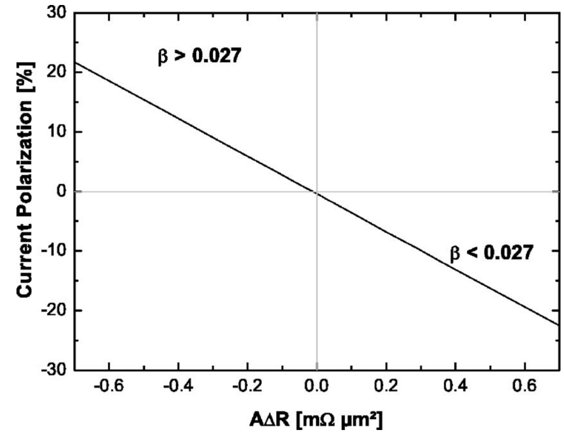

FIG. 10. Current polarization vs absolute magnetoresistance varying the bulk spin asymmetry of Fe(Cr) pinned layer. The interfacial spin asymmetry remains at −0.4.

In Sec. VII we present other calculations illustrating the linear relationship between current polarization due to the pinned layer and absolute MR, varying one CPP parameter.

VII. OTHER SITUATIONS SHOWING LINEAR DEPENDENCE

We extended this type of calculations to other situations not yet explored experimentally. The results are shown in Fig. 11 where we find a linear dependence between absolute CPP-GMR and current polarization due to the pinned layer. In a first case (black line, top axis), we used the sample discussed in Sec. IV and for a 0.45 nm-thick Ru capping layer, we varied the Ru/CoFe interfacial spin flip. This could be experimentally achieved for instance by dusting the interface with Mn impurities. The higher the interfacial spin flip, the higher the current polarization and the absolute MR. In a second case (dotted line, top axis), we used the sample structure of the Urazhdin *et al.*[22] experiment presented in Sec. V and we varied the bulk spin asymmetry of the pinned Py layer, keeping the interfacial spin asymmetry unchanged. This variation could be experimentally realized by introducing a small amount of Cr or *V* in NiFe. This parameter influences directly the current polarization and the CPP-GMR. In a last case (grey line, bottom axis), in the same structure, we find a similar linear behavior when we vary the resistivity of the CuPt layer for a fixed thickness.

Note that in the present calculation which takes into account the complete multilayered stack and spin flip, the calculated current polarization does not generally vanish when absolute CPP-GMR goes to zero. This means that one can

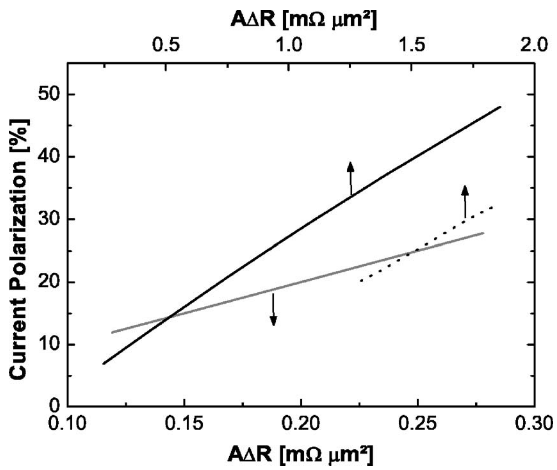

FIG. 11. Calculation of current polarization due to pinned layer vs CPP-GMR, varying different parameters: Ru/CoFe interfacial spin flip in a Jiang *et al.* experimental sample (black line); spin scattering asymmetry of the pinned Py layer in a Urazhdin *et al.* sample (dotted line); CuPt bulk resistivity in a Urazhdin *et al.* sample (grey line).

adjust[33] the CPP parameter in order to cancel either current polarization due to pinned layer (and thus spin torque) or CPP-GMR. This is in contrast with the oversimplified model presented in Sec. II D which gives a flavor of the linear relationship between absolute CPP-GMR and spin torque by considering only two magnetic layers and no spin flip.

VIII. CONCLUSION

We have presented a simple model to understand the main parameters which determine the STT amplitude. This model combines the ballistic picture of the STT in which the STT amplitude is proportional to the polarization of the current impinging on the free layer, with a calculation of this polarization by using the diffusive Valet and Fert model of CPP-GMR. Despite the fact this model does not explicitly take into account the role of spin accumulation in spin torque,[14] it allowed us to interpret a number of experimental results. This simple model explains the linear dependence between the absolute CPP-GMR and inverse switching current, when varying only one parameter, observed in a number of experimental situations. Finally we underline that the linear relationship between CPP-GMR and STT amplitude agrees well with the circuit theory developed by Slonczewski.[17] An extension of this theory will be presented elsewhere[33] in which this linearity is demonstrated.

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