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Citation for published version (APA):

Boulle, O., Kimling, J., Warnicke, P., Kläui, M., Rüdiger, U., Malinowski, G., Swagten, H. J. M., Koopmans, B., Ulysse, C., & Faini, G. (2008). Nonadiabatic spin transfer torque in high anisotropy magnetic nanowires with narrow domain walls. *Physical Review Letters*, 101(21), 216601-1/4. Article 216601. <https://doi.org/10.1103/PhysRevLett.101.216601>

DOI:

[10.1103/PhysRevLett.101.216601](https://doi.org/10.1103/PhysRevLett.101.216601)

Document status and date:

Published: 01/01/2008

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Nonadiabatic Spin Transfer Torque in High Anisotropy Magnetic Nanowires with Narrow Domain Walls

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(Received 28 June 2008; published 19 November 2008)

Current induced domain wall (DW) depinning of a narrow DW in out-of-plane magnetized (Pt/Co)₃/Pt multilayer elements is studied by magnetotransport. We find that for conventional measurements Joule heating effects conceal the real spin torque efficiency and so we use a measurement scheme at a constant sample temperature to unambiguously extract the spin torque contribution. From the variation of the depinning magnetic field with the current pulse amplitude we directly deduce the large nonadiabaticity factor in this material and we find that its amplitude is consistent with a momentum transfer mechanism.

DOI: 10.1103/PhysRevLett.101.216601

PACS numbers: 72.25.Ba, 75.60.Ch, 75.75.+a

The recent discovery that a spin-polarized current can displace a domain wall (DW) through the spin transfer from conduction electrons to the local magnetization [1] has opened up an alternative approach to manipulate magnetization. Current induced domain wall motion (CIDM) has been investigated experimentally so far in detail in permalloy (Py; Ni₈₀Fe₂₀) nanowires characterized by wide DWs (>100 nm) where the spin of a conduction electron is expected to follow adiabatically the magnetization direction as the electron passes across the DW [1,2]. A key question that has been raised is whether the spin transfer effect contains nonadiabatic contributions due to spin relaxation or nonadiabatic transport [2–6]. It was predicted [3,7] that from the efficiency of the spin transfer effect, which is measured by probing the dependence of the DW propagation magnetic field on the injected current, the nonadiabaticity can be deduced. However, in Py nanowires, the complicated 2D spin structures of the DWs prevent direct comparison to 1D models and a meaningful comparison to full 2D micromagnetic simulations is only possible if the exact spin structure during pulse injection is known, which is generally not the case. In particular, the wall deformations and transformations that have been observed [8] can render the results impossible to interpret in terms of the nonadiabaticity.

To obtain simple DW spin structures, out-of-plane magnetized materials with a strong uniaxial anisotropy can be used where the simple Bloch or Néel DW spin structure is more apt for an analysis using an analytical 1D model including the nonadiabatic torque terms. In addition, a larger nonadiabaticity is expected in these materials due to the larger magnetization gradient for such narrow DWs [2,4,9]. This larger nonadiabaticity may explain the high efficiency of the current induced DW depinning reported

recently in such materials [10,11]. However, another major obstacle for the determination of the nonadiabaticity from the dependence of the DW depinning magnetic field on current is that Joule heating strongly affects the thermally activated DW depinning. For experiments carried out at a constant *cryostat* temperature, it is thus hard to extract directly the contribution from the spin transfer torque.

In this Letter we probe CIDM in out-of-plane magnetized (Pt/Co)₃/Pt multilayer structures with narrow and simple DWs to deduce the efficiency of the spin transfer torque effect in this material. We find that for conventional measurements, thermal activation effects conceal the real spin torque efficiency and to unambiguously discriminate between spin torque and heating effects, we employ a special measurement scheme, where the sample temperature is kept constant during pulse injection. These measurements yield the real spin torque efficiency and in a detailed analysis we investigate the underlying physical mechanisms for the nonadiabatic spin torque deduced from our measurements.

The Pt(2 nm)/[Co(0.6 nm)/Pt(1.4 nm)]₂/Co(0.6 nm)/Pt(2 nm) thin film grown on a Si/SiO₂(220 nm) substrate by sputtering is out-of-plane magnetized as confirmed by polar magneto-optical Kerr effect measurements [see Fig. 1(a)]. SQUID magnetometry reveals a saturation magnetization of the film $M_s = 1.4 \times 10^6$ A/m at 300 K. 530 nm wide wires [Fig. 1(b)] along which three 530 × 530 nm² Hall crosses were fabricated by *e*-beam lithography and lift-off [Fig. 1(b), inset]. A 200 nm AlN insulating capping layer with high thermal conductivity was then deposited by sputtering. The position of the DW is detected with high sensitivity in a Hall cross [Fig. 1(b), contacts V^-V^+] by the extraordinary Hall effect (EHE). The Hall voltage is measured using a standard lock-in

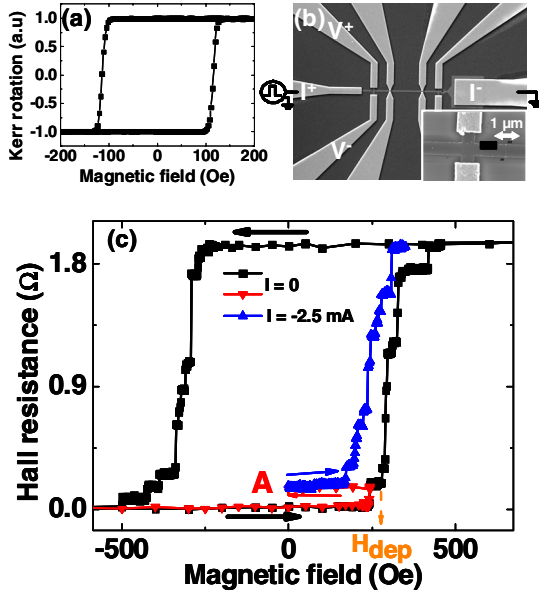


FIG. 1 (color online). (a) Polar Kerr rotation angle as a function of the magnetic field applied perpendicular to the film plane of the unpatterned Pt/(Co/Pt)₃ film at room temperature. (b) SEM image of the structure; inset: SEM image of the Hall cross connected to the gold electrodes. (c) Hall resistance vs the perpendicular applied magnetic field at $T_{cryo} = 180$ K; the black curve (full squares) corresponds to a full hysteresis cycle, the red curve (down triangles) was measured while preparing the magnetic state to plateau A. For the blue curve (up triangles), current pulses of -2.5 mA were injected before measuring the Hall resistance. H_{dep} is indicated for the black curve.

technique with a small ac current ($2 \mu\text{A}$) [Fig. 1(b), contacts I^-I^+].

The effective easy-axis magnetic anisotropy $K_{eff} = K_u - \mu_0 M_s^2/2$ was estimated by measuring the dependence of the EHE signal on an hard-axis in-plane applied field. We deduce $K_{eff} = 2.7 \times 10^5 \text{ J/m}^3$ at 300 K, in line with other reports [12]. Using full 2D micromagnetic simulations [13] (mesh size was $2 \times 2 \text{ nm}^2$) and assuming an exchange constant $A = 1.6 \times 10^{-11} \text{ J/m}$ [14], we estimate a DW width $\Delta = \pi\sqrt{A/K_0} \approx 20 \text{ nm}$ (or using the definition $\sqrt{A/K_0} \approx 6.3 \text{ nm}$) with K_0 the effective out-of-plane anisotropy in the wire. Fig. 1(c) (black line) shows an EHE hysteresis cycle for a magnetic field applied perpendicularly to the layer plane. The reversal in steps indicates that the switching occurs through the propagation of a DW successively pinned at different positions inside the cross. The position of the steps varies from one Hall cross to another, which indicates that these steps mainly originate from pinning sites due to natural defects in the film or edge irregularities.

To study the effect of current pulses on the DW depinning, we first pin a DW at a pinning center localized at the entrance of the Hall cross corresponding to the plateau labeled A in Fig. 1(c) by using the magnetic field sequence associated with the red $R_{Hall}(H)$ curve. It should be stressed

that this plateau in the EHE can be reproducibly attained over a large temperature range between 4.4 K and room temperature. Starting from zero field, we then increase the magnetic field in steps of 2 Oe. After each step, a current pulse (length $50 \mu\text{s}$) is injected into the wire [(contacts I^- , I^+), Fig. 1(b)] with a large rise time ($18 \mu\text{s}$). Finally, the Hall resistance is measured.

We present in Fig. 1(c) (blue curve) the resulting $R_{Hall}(H)$ curve for $I = -2.5 \text{ mA}$. The injection of the current pulses here leads to a decrease of the depinning field H_{dep} for which a jump from the plateau A in the $R_{Hall}(H)$ curve is observed. In Fig. 2(a) we plot $H_{dep}(|I|)$ for a cryostat temperature of 130 and 250 K for positive and negative currents. For both temperatures, H_{dep} is first approximately constant with $|I|$ for a low current; for a higher current, H_{dep} decreases rapidly with $|I|$ whatever the current polarity although it is higher for positive than for negative currents. As usual, we define the efficiency ϵ as the slope $|\mu_0 \Delta H_{dep} / \Delta J|$ that describes the equivalent effective field felt by the DW due to the presence of current [10,11]. For a current distribution approximately uniform across the magnetic film, 1 mA corresponds to a current

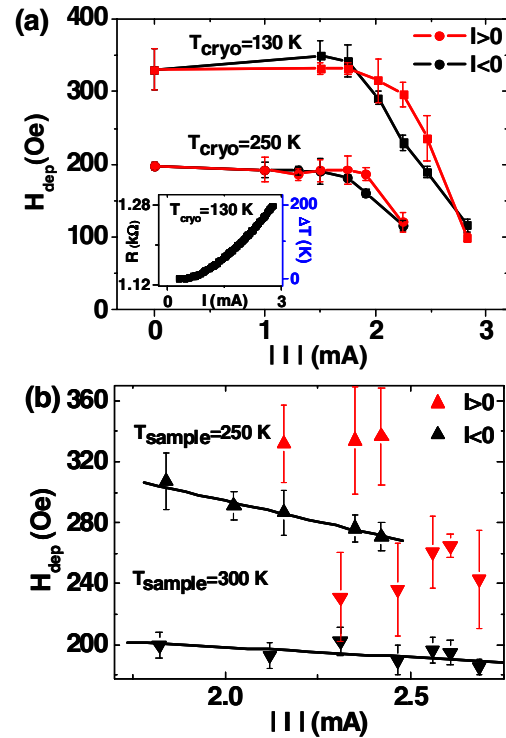


FIG. 2 (color online). (a)–(b) H_{dep} as a function of $|I|$ for (a) a constant cryostat temperature of $T_{cryo} = 130$ K (squares) and $T_{cryo} = 250$ K (circles) and (b) a constant sample temperature of $T_{sample} = 250$ K (up triangles) and $T_{sample} = 300$ K (down triangles). Each point corresponds to the mean value of H_{dep} averaged over 10 measurements or more and the error bars show the standard deviation. In (b), the black lines are a linear fit of the data. Inset in (a): dependence of the resistance and of the sample temperature rise ΔT with the current for $T_{cryo} = 130$ K.

density $J = 2.2 \times 10^{11}$ A/m². This leads to $\epsilon_{\text{Co/Pt}} = 9.7 \times 10^{-14}$ Tm²/A at 130 K and $\epsilon_{\text{Co/Pt}} = 5.9 \times 10^{-14}$ Tm²/A at 250 K for negative current, about 1 order of magnitude higher than the one deduced by a similar method in permalloy nanowires [15] ($\epsilon_{\text{Py}} \approx 5 \times 10^{-15}$ Tm²/A).

Figure 2(a) suggests that two distinct effects are involved in the DW depinning: a first effect that is independent of the current polarity, likely to be due to Joule heating and a second one that depends on the sign of the current. To clarify this point and separate both contributions, we employ a special experimental scheme to carry out all the following measurements at a constant temperature of the *sample*. First, the sample temperature is determined by using the four-point resistance of the wire during current injection as a thermometer [16] with the same method as described in Refs. [15]. As an example, the resistance and corresponding temperature rise ΔT is shown in the inset of Fig. 2(a) as a function of I for a cryostat temperature of $T_{\text{cryo}} = 130$ K. The temperature increases approximately quadratically with I and can reach values up to 200 K for the maximum injected current. This information is then used to adjust the injected current so that for each cryostat temperature the sample temperature is constant.

We present in Fig. 2(b) $H_{\text{dep}}(I)$ for a constant sample temperature $T_{\text{sample}} = 250$ K (up triangles) and $T_{\text{sample}} = 300$ K (down triangles). We start with $T_{\text{sample}} = 250$ K, where the behavior is very different from the one observed for a constant cryostat temperature: H_{dep} decreases with $|I|$ for a negative current ($H_{\text{dep}}^-(I)$) but not for a positive current ($H_{\text{dep}}^+(I)$), where it shows only little change with $|I|$ and $H_{\text{dep}}^+(I) > H_{\text{dep}}^-(I)$. Current thus makes the depinning easier only for one current polarity. The dependence of H_{dep} on $|I|$ for negative current as well as the different behavior for both current polarities clearly demonstrate that this effect is not due to Joule heating. A real efficiency $\epsilon \approx 2.5 \times 10^{-14}$ Tm²/A results, that is smaller than the one that can be deduced for a constant cryostat temperature at 250 K. If we compare this value to the one deduced from the $T_{\text{cryo}} = 130$ K $H_{\text{dep}}(|I|)$ curve for $I = 2.25$ mA corresponding to $T_{\text{sample}} = 250$ K, we see that the Joule heating contributes to about 75% of the depinning efficiency measured with the conventional approach at a constant cryostat temperature. Thus Joule heating plays here an important role in the DW depinning and it is clear that measurements at a constant cryostat temperature do not allow one to determine the pure effect of the spin transfer torque. The $H_{\text{dep}}(I)$ curve at $T_{\text{sample}} = 300$ K is qualitatively similar to the one obtained at $T_{\text{sample}} = 250$ K although the dependence of H_{dep} on $|I|$ is much weaker for negative current with $\epsilon \approx 6.0 \times 10^{-15}$ Tm²/A.

Several mechanisms may lead to the current polarity dependent variation of the depinning field for the constant sample temperature experiment. First, we consider the DW drag [18,19] creating a perpendicular magnetic field $B_z \propto$

$\tan(\theta_h)J$, with θ_h the Hall angle. Using the expression of B_z proposed by Viret *et al.* [19], and $\tan\theta_h \approx 0.025$ measured experimentally, we obtain an efficiency $\epsilon = B_z/J \approx 2.3 \times 10^{-16}$ Tm²/A, i.e., at least 1 order of magnitude smaller than the one we measure at T_{sample} equal to 250 K or 300 K. Therefore this effect cannot explain our observation. Second, the Oersted field generated by the current might play a role, but the resultant force on the DW is zero, and so this effect should be negligible. Furthermore, the Oersted field should be the same for T_{sample} equal to 250 K or 300 K and therefore it cannot explain the decrease of the efficiency for increasing T_{sample} .

Third, we consider the adiabatic spin transfer torque proposed by Berger [1] and more recently by Tataru *et al.* [2]. We note first that our experiments correspond to the low pinning case discussed by Tataru *et al.* [2] expected if $H_{\text{pin}} < H_k/\alpha$, with H_{pin} pinning field, H_k the hard-axis anisotropy field and α the Gilbert damping. Indeed, we estimate $H_{\text{pin}} \sim 470$ Oe from the $H_{\text{dep}}(T)$ curves much smaller than $H_k/\alpha \approx 5000$ Oe with $\alpha \sim 0.15$ in our films [20,21] and $\mu_0 H_k \approx 0.075$ T for our 530 nm wide wire deduced from hard-axis magnetometry combined with 2D micromagnetic simulations [13]. In addition, for our quasistatic 18 μs pulse rise time, we do not expect any subthreshold dynamical depinning [1,22]. Thus, depinning should only occur at the critical current density J_c for steady motion associated with the ‘‘intrinsic pinning’’ due to the DW demagnetizing energy [2]. In the rigid DW approximation [3], $J_c = eM_s\mu_0 H_k(A/(K_0 + K/2))^{1/2}/(\hbar P)$, with P the polarization of the current, and $K = \mu_0 M_s H_k/2$. For $P = 0.46$ in Co, we obtain $J_c = 2.1 \times 10^{12}$ A/m² much higher than the lowest current density for which CIDM was observed ($J \approx 4 \times 10^{11}$ A/m²). Moreover, the strong decrease of H_{dep} with $|I|$ for negative current is not compatible with a purely adiabatic spin torque. Indeed, J_c should not depend on H in the adiabatic case at all for our quasistatic current pulse (as also predicted by numerical simulations) since H does not change the demagnetizing energy of the pinned DW, that controls the current induced depinning under this assumption [23]. We therefore conclude that the adiabatic spin transfer torque cannot account for our experimental results.

Thus, what remains as a possible explanation are torque terms beyond the adiabatic term: the torque due to the spin relaxation in the wall described by the dimensionless parameter β^{SR} [3,5] and the torque due to a higher order nonadiabatic correction whose effect is equivalent to a momentum transfer from the conduction electron to the DW (parameter β^{NA}) [2,6]. These torques exert a force on the wall similar to the effect of an effective perpendicular magnetic field B with $B/J = \epsilon = \beta P \hbar \pi / (2e M_s \Delta)$ with $\beta = \beta^{\text{SR}} + \beta^{\text{NA}}$. Such a behavior is in qualitative agreement with the linear variation of the depinning field with current I .

From the efficiency derived in our experiment for negative current at constant sample temperature, we obtain

$\beta \approx 1.45$ at 250 K and $\beta \approx 0.35$ at 300 K. For the spin relaxation mechanism, several theoretical approaches [6] predict β^{SR} to be of the order of the damping parameter α , which is about 0.15 in our films [20,21]. These values are significantly lower than the β we deduced experimentally [24]. So a possible remaining effect is the momentum transfer mechanism. The parameter β^{NA} in the ballistic limit is a function of the domain wall resistance [2] R_{DW} with $\beta^{\text{NA}} = e^2 n A R_{\text{DW}} \Delta / P \hbar \pi = e^2 n \rho_{\text{DW}} \Delta^2 / P \hbar \pi$ with n the electron density, A the lateral cross section of the wire, $\rho_{\text{DW}} = R_{\text{DW}} A / \Delta$ the DW resistivity. For $n = 5.6 \times 10^{28} \text{ m}^{-3}$ in Co [25], a DW resistivity $\rho_{\text{DW}} = 3.9 \times 10^{-10} \Omega \text{ m}$ can be derived from the $T_{\text{sample}} = 250 \text{ K}$ β value ($\rho_{\text{DW}} = 0.9 \times 10^{-10} \Omega \text{ m}$ for $T_{\text{sample}} = 300 \text{ K}$) that agrees with the DW resistivity measured by Aziz *et al.* [26] in similar Pt(3.5 nm)/Co(0.6 nm)/Pt(1.6 nm) structures at room temperature ($\rho_{\text{DW}} = 2.3 \times 10^{-10} \Omega \text{ m}$). The momentum transfer is thus a possible mechanism to explain our experimental results. We note, however, that momentum transfer due to nonadiabaticity is predicted [4,6,27] to be small for our DWs with widths that are large compared to the Fermi wavelength and larger than the Larmor precession length [4,6] or the mean free path [27] and this calls for further theoretical works [28].

It should also be noted that the nonadiabatic spin torque effect term predicts a symmetric behavior with the current polarity; i.e., the decrease in the depinning field for a negative current should be equal to the increase for a positive current. We see in Fig. 2(b) that we do not observe a completely symmetric behavior. In particular, the distribution of the depinning field, marked by the error bars in Fig. 2(b) is always smaller for negative currents, where current helps to depin the DW, than for positive currents and this behavior is observed consistently but is presently not well understood. Furthermore only a clear decrease of H_{dep} is observed for negative current. This suggests that an additional effect is involved in the current induced depinning process that seems to help the DW depinning whatever the current polarity.

Finally, the models invoked so far do not explain the strong decrease of the efficiency observed as the sample temperature increase from 250 to 300 K since we expect little variation of Δ , M_s , ρ_{DW} [30] or spin relaxation rate in this small temperature range. For Py, Laufenberg *et al.* [15] observed a corresponding increase of the zero field critical current with sample temperature. This can be attributed to the onset of thermally activated spin waves that effectively carry away angular momentum [31], which may explain the observed reduction of the efficiency with increasing temperature in our case.

In conclusion, we have used a special measurement scheme to investigate spin transfer in high anisotropy out-of-plane magnetized (Pt/Co) multilayer elements with narrow domain walls. We determine the real efficiency of the spin transfer torque effect from measurements of the depinning field as a function of the current

pulse amplitude at a constant sample temperature. This has not been possible previously using conventional measurements at a constant cryostat temperature where, as we directly demonstrate, thermal activation effects dominate. From the real efficiency, the nonadiabaticity of the spin transfer is determined in this material and we find that our observations are consistent with a momentum transfer mechanism.

The authors thank G. Tatara and M. Stiles for useful discussions and acknowledge support by the Samsung Advanced Institute of Technology, the DFG (SFB513 and SFB767) and the EU (ERC-2007-StG208162 and SPINSWITCH MRTN-CT-2006-035327).

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