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Current-induced domain wall motion in Co/Pt nanowires: Separating spin torque and Oersted-field effects

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We report on low temperature current induced domain wall depinning experiments on (Co/Pt) multilayer nanowires with perpendicular magnetization. Using a special experimental scheme, we are able to extract the different contributions of the Oersted field and spin torque from the dependence of the depinning field on the injected current for selected magnetization configurations. The spin torque contribution is found to be dominant with a small contribution of the Oersted field leading to a nonadiabaticity factor β in line with previous measurements.

Current induced domain wall motion (CIDM) in ferromagnetic nanoscale wires holds promises for applications in the field of data storage or logic devices[1,2] and was observed by a number of groups.[3–7] Recent studies on materials with perpendicular anisotropy have revealed a higher efficiency for CIDM than in the case of in-plane magnetized materials.[8–11] Especially the contributions of the adiabatic[12,13] and nonadiabatic spin torque due to spin relaxation[14–16] or momentum transfer[12,14] to the domain wall (DW) motion and their dependence on the material properties are so far not fully understood. In particular, studies on Co/Pt multilayers show a large nonadiabaticity factor β.[7,17,18] The microscopic origin of this large value is still under debate.

In addition to the spin torque, the injection of the current leads to an additional Oersted field concentric around the wire axis. The amplitude of this Oersted field can be large at the wire edges and may significantly affect the DW dynamics as well as the domain structure within the wire. This was shown for example in a recent study on CoFeB/Pt multilayers.[19] In general, for the determination of the spin torque terms, the contribution of Oersted field to the DW displacement needs to be ascertained to separate the different contributions and this is still lacking for out-of-plane magnetized materials. The resulting force from the Oersted field on a DW in thin in-plane magnetized materials is zero and therefore does not affect the DW displacement.

In this paper we present CIDM transport measurements in Co/Pt multilayer nanowires with perpendicular anisotropy employing the extraordinary Hall effect (EHE).[20] By making use of the distinct symmetries of the effects of the Oersted field, Joule heating and spin torque, their contributions to the DW depinning are unambiguously extracted. This allows us to deduce the amplitude of the nonadiabaticity factor β excluding Oersted field effects. We find a value for β, which is in line with earlier measurements.

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The structure studied is a 290 nm wide wire, which was fabricated by e-beam lithography and lift-off. The material used is a Pt(2 nm)/[Co(0.6 nm)/Pt(1.4 nm)]$_2$/Co(0.6 nm)/Pt(2 nm) multilayer structure, which was grown on a Si/SiO_2(220 nm) substrate by sputtering. To improve heat dissipation, a 200 nm thick AlN layer with high thermal conductivity was deposited on top of the structure.

To monitor the position of the DW in the Hall cross, we use the extraordinary Hall effect[7,21] [Fig. 1(b)]. A small ac current (2 μA) generated by a lock-in amplifier is applied between the contacts I_+ and I_-, while the extraordinary Hall voltage is being measured between the contacts V_+ and V_- [Fig. 1(b)]. The Hall resistance R_{Hall}, is a measure for the wall position as it is proportional to M_z, the out-of-plane component of the magnetization.

Prior to the current injection, a DW is created and pinned in the Hall cross using the following field sequence: First we saturate the wire by applying a perpendicular external field [Fig. 1(a), sketch I or III] and relaxing it back to zero. Then the field is slowly increased in the opposite field direction

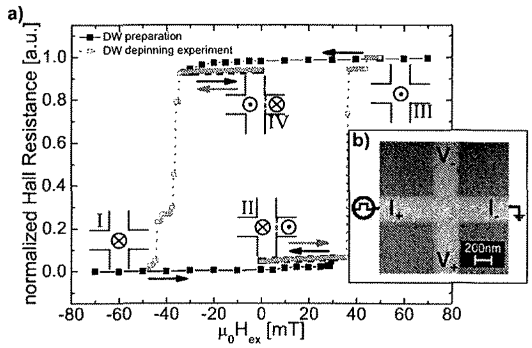

FIG. 1. (Color online) (a) Normalized Hall resistance as a function of the applied perpendicular external field at a constant cryostat temperature $T_{\mathrm{Cryo}}=100$ K. The curves with filled squares and solid lines correspond to the preparation of the DWs, while each point of the curves with open squares and dotted lines is measured after the injection of a single pulse with a current density of $J=1.02\times10^{10}$ A/m^2. (b) Scanning electron microscopy image of the Hall cross used to detect the position of the DW. The current (I) and voltage (V) contacts are indicated.

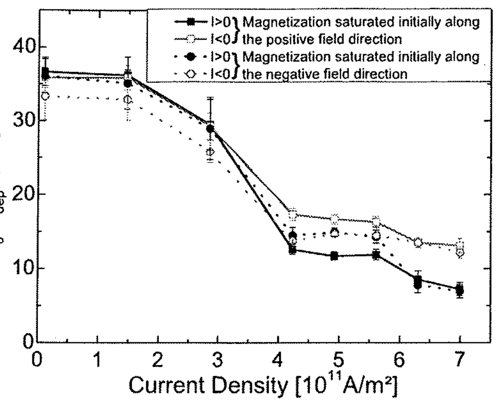

FIG. 2. (Color online) $|H_{dep}|$ as a function of the injected current density for a constant cryostat temperature $T_{Cryo}=100$ K and for both initial magnetization configurations. The measurement points represent the mean values of $|H_{dep}|$ averaged over at least eight repetitions, while the error bars show the standard deviation.

until a 5% threshold change in the Hall resistance is observed, indicating that a DW enters the Hall cross [Fig. 1(a), black curves (filled squares, solid lines)]. When this threshold is reached, the external field is again relaxed to zero and the DW stays pinned at the entrance of the Hall cross [Fig. 1(a), sketch II or IV], which is reflected in the constant value of R_{Hall}.

To determine the depinning field H_{dep} of the DW at the prepared position, we increase the external magnetic field in steps of 0.5 mT and inject a single 50 μs pulse with a slow rise time (18 μs) into the wire between contacts I_+ and I_- after each field step [Fig. 1(a), red curves (open squares, dotted lines)]. The domain wall motion is monitored by measuring the Hall resistance after each current pulse [Fig. 1(a), red curves (open squares, dotted lines)]. The field at which the value of the normalized Hall resistance passes the threshold value of 10% of the normalized Hall resistance for positive fields (or goes below 90% for the negative field direction) is then defined as the depinning field H_{dep}. This low threshold value allows for the detection of a jump of the DW from the initial pinning site. Two examples for normalized R_{Hall} curves using positive or negative fields during the preparation of a DW (black curves [filled squares, solid lines]) and the injection of current pulses with a current density $J=1.02\times 10^{10}$ A/m^2 [red curves (open squares, dotted lines)] are presented in Fig. 1(a).

The absolute value of the depinning field $|H_{dep}|$ as a function of the injected current density for a constant cryostat temperature $T_{Cryo}=100$ K is shown in Fig. 2. The experiment was first carried out for an initial magnetization along the negative field direction and a positive field was applied during the depinning measurements for two current polarities (I_+ and I_-) [Fig. 1(a), sketch II]. In Fig. 2 (solid lines) it can be seen that the measured depinning fields stay almost constant for small current densities, followed by a rapid decrease for higher current densities independent of current polarity, which can be attributed to Joule heating.[7] For current densities larger than 4×10^{11} A/m^2 a clear splitting between the two current polarities is observed, suggesting that effects beyond heating and depending on the current polarity become significant. For this long rise time current pulses, the effect of the adiabatic torque on the DW depinning was shown to be negligibly small.[7,22]

Two remaining effects may lead to such a polarity dependent behavior: the nonadiabatic spin transfer torque, which exerts a force on the DW in the direction of the electron flow,[7] and the Oersted field. The Oersted field can significantly affect the DW depinning, in particular, if the DW is preferentially pinned at one edge of the wire, for instance due to edge roughness. Due to its symmetry, the Oersted field effect on the DW depinning depends on the direction of the magnetization (M_- or M_+) in the domains adjacent to the DW and will favor the depinning in opposite directions, if the magnetization is reversed [for instance for the situations sketched as II and IV in Fig. 1(a)]. This allows one to clearly separate both contributions by repeating the same CIDM experiment but for opposite orientations of the magnetization in the domains. So in the second set of experiments, the initial magnetization is along the positive field direction and a negative field is applied during the depinning experiment [starting with the configuration sketched as IV in Fig. 1(a)]. This inverts the order of the magnetization within the Hall cross as it is shown in Fig. 1(a) (sketch IV). The resulting depinning fields are shown in Fig. 2 (dotted lines). The Oersted field, Joule heating and spin torque contributions can now easily be extracted from these experiments from the symmetry considerations.

The change in the depinning field induced by the Oersted field (H_{Oe}) is inverse, when the current polarity or the magnetization in the domain is reversed so that $H_{Oe}(I_+,M_+)=-H_{Oe}(I_+,M_-)$ and $H_{Oe}(I_+,M_+)=-H_{Oe}(I_-,M_+)$, where M_+ (respectively M_-) stands for the initial magnetization configuration II (respectively IV).

On the contrary, the spin torque acts similar to an effective magnetic field (H_{ST}),[7] which is independent of the magnetization configuration M. This can be expressed by the following relations: $H_{ST}(I_-,M_+)=H_{ST}(I_-,M_-)=-H_{ST}(I_+,M_+)$.

The dominant Joule heating effect is independent of external field direction and current direction, which creates an effective field $H_{Joule}(|I|,|M|)$ supporting the depinning in any case. The variation in the depinning field due to the current injection is the sum of these three fields: $H_{dep}=H_{ST}+H_{Oe}+H_{Joule}$.

One can show easily that $H_{ST}=\{[H_{dep}(I_+,M_+)-H_{dep}(I_-,M_+)]+[H_{dep}(I_+,M_-)-H_{dep}(I_-,M_-)]\}/4$, while the Oersted field contribution can be deduced as $H_{Oe}=\{[H_{dep}(I_+,M_+)-H_{dep}(I_-,M_+)]-[H_{dep}(I_+,M_-)-H_{dep}(I_-,M_-)]\}/4$.

The results for H_{ST} and H_{Oe} are shown in Fig. 3. We see that H_{ST} arising from the spin torque effect increases with increasing current density, showing values of up to 2.77 mT for current densities larger than 4×10^{11} A/m^2, whereas the Oersted field contribution stays close to zero.

A quantitative description of the spin torque is obtained by analyzing the efficiency ϵ, which is defined as the slope $|\mu_0\Delta H_{dep}/\Delta J|$. A linear fit results in an efficiency $\epsilon=(4.09\pm 0.2)\times 10^{-15}$ Tm^2/A. The nonadiabaticity factor β can be deduced from the efficiency by using the relation $\epsilon=\beta P\hbar\pi/(2eM_S\Delta)$,[7] with P the polarization of the current and Δ the DW width. From our derived efficiency we obtain $\beta\approx 0.24$. The previously measured β-value at a constant sample temperature of $T_{sample}=300$ K is $\beta\approx 0.35$.[7] Taking into account only the nonzero values of the Oersted field, a linear fit would lead to maximum Oersted field contribution with the efficiency $\epsilon=(2.49\pm 0.2)\times 10^{-15}$ Tm^2/A, which is

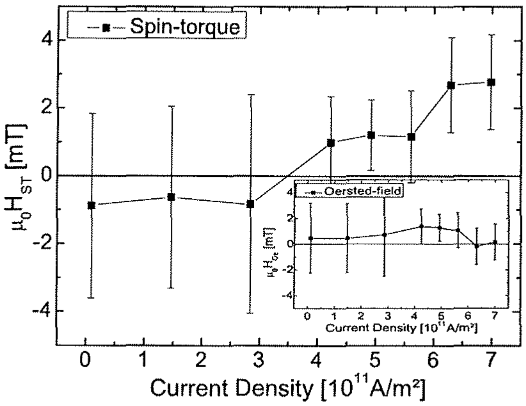

FIG. 3. The deduced contributions for spin torque and for Oersted field (inset). The efficiency ϵ is deduced from a linear fit through the origin (zero spin torque for zero current density) using the points with the lowest Oersted field contribution.

significantly smaller than the efficiency derived from spin torque.

It should be noted that our measurements were carried out at a constant cryostat temperature $T_{\mathrm{Cryo}}=100$ K. In this case we have to take into account that the injection of high current densities leads to local heating in our structure. Previous measurements on 530 nm wide wires[7] showed a temperature increase of more than 200 K for injected current densities larger than 6×10^{11} $\mathrm{A/m^2}$, which are similar to the higher current densities we injected in this measurement here. The wire of our present work is narrower (290 nm), therefore less current is needed to create the same current densities. A smaller power produces less heating but the reduced heat dissipation due to the also reduced surface compared to the wider wire compensates this, leading to the expectation of a similar temperature increase ($\Delta T > 200$ K) in our case. Therefore the injection of high current densities ($>6\times 10^{11}$ $\mathrm{A/m^2}$) leads to a temperature increase in the structure up to 300 K starting from the constant cryostat temperature of $T_{\mathrm{Cryo}}=100$ K. The comparison of our measured $\beta\approx 0.24$ with the previous one at the constant sample temperature ($T_{\mathrm{sample}}=300$ K) experiment ($\beta\approx 0.35$)[7] shows a good agreement.

In summary our measurement scheme allows to clearly separate the spin torque and Oersted field contributions in current induced domain wall depinning experiments. The deduced efficiency of the spin transfer torque is in good agreement with previous work, showing that the high spin torque efficiency is intrinsic to the material and not stemming from other spurious effects.

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