Extraction of the spin torque non-adiabaticity from thermally activated domain wall hopping

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We investigate the non-adiabaticity of current-induced domain wall motion by time resolved analysis of thermally activated domain wall motion between two metastable states within a Co/Pt multilayer wire with a strong uniaxial perpendicular anisotropy. By measuring the dwell times for which the domain wall remains in one state we deduce the non-adiabaticity factor β using two independent approaches: (i) the dependence of the dwell times on the injected current and (ii) the current-field equivalency. The comparison of the results allows us to gauge their reliability and the observed differences highlight the importance of the 2D nature of the domain wall.

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The injection of a current into ferromagnetic materials opens a new way to probe and manipulate locally the magnetization. In combination with modern nano-fabrication methods it enables the invention of new magnetic storage and logic devices.[1,2] Several theoretical investigations related to the spin torques (adiabatic[3] and non-adiabatic[3–5]) acting on a domain wall (DW) in ferromagnetic nanowire structures have been carried out. As the performance of such devices is governed by the torques, the understanding and origin of the torques and ways to measure them are at the heart of current spin torque research. However, in order to reliably ascertain values for the non-adiabaticity parameter β, one needs robust methods to determine β. Many measurements of the non-adiabatic torque and the search for its origin have been carried out for soft in-plane magnetized materials by a number of groups[6–11] using different techniques. Recently the focus has shifted to out-of-plane magnetized wires, where a larger non-adiabaticity can be expected due to the large magnetization gradients.[12] Different techniques have also been used for these materials, but due to the fact that most of the dynamics take place in the creep regime, these approaches are mostly different from the ones used for soft magnetic materials. One method that has been used is based on the displacement of DWs in the creep regime under applied fields and currents.[13] This method relies on knowing the distance of the DW motion and small values of $\beta \approx \alpha$ were claimed.

An alternative approach is to use the field-current equivalency[14–17](for details see Eq. 2 later on): This method was used by Boulle et al.,[14] where the change in depinning field as a function of injected current density was analyzed. Here, the measurements revealed a large non-adiabaticity factor of $\beta = 0.35$ to 1.45 depending on the temperature. To mitigate the Joule heating problem, the cryostat temperature was adjusted to obtain a constant sample temperature, but this requires cumbersome measurements and of course entails large temperature changes of the sample between current pulses. Furthermore, the problem of possible Oersted field contributions exists in this approach, but employing depinning field measurements at a constant cryostat temperature using two different initial magnetization configurations allows for the distinction between the spin torque and the Oersted field contribution confirming values of $\beta > \alpha$[18]. So there is a clear discrepancy between the values extracted from the different approaches ($\beta \approx \alpha$ or $\beta > \alpha$) and it is unclear whether this is due to the different samples used or due to the different methods that do not extract exactly the same information. To determine whether it is the sample or the method that leads to the different values of β, one needs to ideally use the different methods on the same sample.

Furthermore, experiments with low current densities are necessary to exclude Joule heating effects. So far in particular the field-current equivalency method has been used when large current densities are injected to see clear effects, but recently a promising approach based on thermally activated DW hopping has been pioneered.[6]

In this paper, we use thermally activated DW motion experiments to deduce β by studying the motion under the influence of combined currents and fields. We present time resolved measurements of the extraordinary Hall effect, which is commonly used to detect domain reversal processes in out-of-plane magnetized wire structures and allow one to determine the DW position with high spatial resolution. Time resolved measurements on a sample with two metastable pinning sites for a DW enable us to deduce the effect of small currents and fields due to the exponential dependence of the dwell times for which the domain wall remains in one state.[19] We are able to use the current-field equivalency method by measuring the effects of concurrently applied small fields and currents with high accuracy and extract β from this. Furthermore, from the dwell times as a function of the current we can also determine β if the displacement distance is known and we compare both approaches to gauge their validity.

A Hall cross was patterned along a 500 nm wide wire by e-beam lithography and lift-off (for details see Ref. 14). The $\mathrm{Pt}(2\,\mathrm{nm})/[\mathrm{Co}(0.6\,\mathrm{nm})/\mathrm{Pt}(1.4\,\mathrm{nm})]_2/\mathrm{Co}(0.6\,\mathrm{nm})/\mathrm{Pt}(2\,\mathrm{nm})$ multilayer structure was grown on a $\mathrm{Si/SiO_2}(220\,\mathrm{nm})$ substrate by sputtering. The effective easy-axis magnetic anisotropy $\mathrm{K_{eff}} = 2.7 \times 10^5\,\mathrm{J/m}$ (at 300 K) was determined previously.[14] Assuming the exchange constant $\mathrm{A} = 1.6 \times 10^{11}\,\mathrm{J/m}$,[20] we can estimate the DW width $\lambda = \sqrt{\frac{\mathrm{A}}{\mathrm{K_{eff}}}} \approx 6.3\,\mathrm{nm}$.

At a constant cryostat temperature of $296.6 \pm 0.1\,\mathrm{K}$ we inject a small DC current ($< 2 \times 10^{11}\,\mathrm{A/m}$) along the wire and use a differential voltage preamplifier and an oscilloscope to monitor the extraordinary Hall voltage time resolved (see Fig. 1 (inset)). The high sensitivity of this effect to the out-of-plane component of the magnetization allows us to precisely determine the signal of the DW entering the Hall cross. To nucleate a DW, we saturate the whole structure by applying an external out-of-plane field and relaxing it back to zero. Slowly increasing the field in the opposite direction leads to a change in the time resolved extraordinary Hall voltage. As in previous experiments[14,18] we are able to pin the DW within the Hall cross by relaxing the field back to zero before a complete reversal of the magnetization within the Hall cross occurs. We then find that at zero field the extraordinary

Hall voltage changes stochastically due to thermally activated DW hopping between pinning sites. We focus in particular on situations where we find two well-defined metastable states between which the DW moves back and forth (Fig. 1 (inset)). We record the extraordinary Hall signal for several minutes before changing the applied field or DC current to obtain sufficient statistics of the dwell times. This is repeated for several combinations of current density, polarity and field amplitudes.

For each set of constant current and field we extract the dwell times for which a DW is staying in each state (τ_0 and τ_1 are the measured average values). The dwell times can also being deduced by using the cumulative distribution function $F(t) = 1 - e^{(-\frac{t}{\tau})21}$ and we find consistent results using both approaches. Fig. 1 shows as an example the normalized cumulative distributions at a constant field (3.41 G) and a constant current (-0.5 mA) for both states. The function $F(t)$ fits well the experimental data, which shows that a single transition path for the DW is present.

Now we turn to the determination of the values of β using the two approaches of the current-field equivalency and the dwell time dependence of the hopping displacement on the current. To use the current-field equivalence, we first determine that we are in a regime, where the depinning is governed by β. Using the definition of the pinning regimes as defined by Tatara et al.[22] we can show that this used approach is valid in our weak pinning regime Ib (details see Ref. 22). We plot in Fig. 2a the $\ln(\frac{\tau_1}{\tau_0})$ as a function of the external applied field for different constant currents. For each constant current density J we use a linear fit and the resulting average slope ξ to deduce the intercepts γ_J with the Y-axes. By simply solving the equation

$$\xi \mathrm{H} + \gamma_{+\mathrm{J}} = \xi(\mathrm{H} + \Delta\mathrm{H}) + \gamma_{-\mathrm{J}} \tag{1}$$

we are able to calculate the shift in field ΔH between different current densities (see Fig. 2a). By dividing the shift in field by the shift in current, we are able to deduce the current-field equivalence defined by the efficiency

$$\epsilon = \left|\frac{\Delta\mathrm{H}}{\Delta\mathrm{J}}\right| = \frac{\beta \mathrm{P}\hbar}{2\mathrm{e}\mathrm{M}_\mathrm{S}\lambda} \tag{2}$$

with $\mathrm{P} = 0.46$ the polarization of the current and $\mathrm{M}_\mathrm{S} = 1.4 \times 10^6\,\mathrm{A/m}$. This equation is used to calculate the non-adiabaticity factor β.[4,14] We find an average value of $\beta_\mathrm{effective} = 0.13 \pm 0.02$ by taking into account all possible combinations of ΔH and ΔJ and considering the errors as weighting factors. We have repeated the experiment for other hopping positions and to slightly lower temperatures ($287.2 \pm 0.1\,\mathrm{K}$) and find values for β between 0.13 and 0.23. These values are consistent with what was measured using the field-current equivalence at larger current densities.[14,18]

Now we compare these results to measurements of the dwell times for the hopping at constant fields as a function of current (see Fig. 2b) that allow us to independently determine the non-adiabaticity factor β. To carry out the analysis we follow the approach of the Arrhenius law, where the DW is described as a particle moving between two metastable states of a 1D-potential separated by a single energy barrier ϵ.[19] Using the relation $\ln(\frac{\tau_1}{\tau_0}) = \ln(\frac{\tau_{0,1}}{\tau_{0,0}}) + \frac{\epsilon_{0,1}-\epsilon_{0,0}}{\mathrm{k_B T}} + \sigma \mathrm{J}$ with $\sigma = \frac{2\mathrm{A}\hbar\beta \mathrm{P X_0}}{\mathrm{k_B T e}\lambda}$ [see Ref. 6] we are able to calculate β if all the parameters are known. In order to do so, it is essential to determine the distance $\mathrm{X_0}$ of the DW displacement between both states and to estimate the cross-sectional area A of the DW. Therefore we measure a complete hysteresis loop ($\Delta\mathrm{R} \approx 1.1\,\Omega$) for a constant current density. From the time resolved measurements we measure the change in the extraordinary Hall voltage between both states as $\Delta\mathrm{R_{states}} \approx 0.032\,\Omega$. Taking into account the width of the hall cross the hopping distance is therefore roughly $\mathrm{X_0} \approx 14.5\,\mathrm{nm}$ assuming a straight wall moving as a rigid object. The cross-sectional area is calculated as wire width multiplied with the thickness, which might not hold for a DW that is not straight. From the slope σ we now derive the non-adiabaticity factor $\beta_{\mathrm{Arrhenius}} = 0.013 \pm 0.001$, which turns out to be one order of magnitude smaller than $\beta_{\mathrm{effective}}$ determined from the field-current equivalency.

This means that we find consistent values for $\beta_{\mathrm{effective}}$ in line with previous measurements, but for $\beta_{\mathrm{Arrhenius}}$ we obtain different values being one order of magnitude smaller. This can also explain, why smaller values of β have been observed in previous experiments that rely on the second type of analysis.[13] To understand where the discrepancy comes from, one needs to look at the unknown parameters that enter into the analysis. Both methods are based on the assumption that the DW dynamics can be described by the 1D-model. But studying DWs within a Hall cross, where deformations of a DW have been observed, might mean that the rigid DW assumption necessary for a definition of $\mathrm{X_0}$ does not hold. Such a change of dimensionality has also been shown by Kim et al.,[23] where a transition from 1D- to 2D behavior in the scaling criticality of creep DW motion as a function of the wire width has been observed. It is also shown, that the activation volume, which is related to the hopping distance, is not proportional to the wire width in the 2D regime. This might also apply in our case and therefore a large uncertainty of the displacement distance X_0

might be present, which we estimated from the extraordinary Hall effect assuming a rigid wall displacement. So for a more accurate determination one then needs to examine the hopping distance via time resolved magnetic imaging to calculate a more precise value for β. Also full micromagnetic simulations at finite temperatures by Garcia-Sanchez et al.[24] have shown that the effective deduced activation volume can be smaller than assumed from the hopping distance in the 1D model, so that one should also go beyond the analytical 1D model when using this analysis approach.

Finally, we can exclude that adiabatic torque effects play an important role, as the current densities used are far too small compared to the critical current density where the Walker breakdown occurs, which is the threshold above which the adiabatic torque rules the dynamics ($J_W \approx 2 \times 10^{12}$ A/m).[14]

In conclusion, we study time resolved measurements of thermally activated DW motion under the influence of an external field and low current densities. The variation of both, current and field, allows us to use two theoretical approaches to extract the non-adiabaticity factor β at the same time on one sample. We derive two different β values varying by an order of magnitude highlighting possible problems when using 1D-models for systems with 2D-dynamics. We find that the precise knowledge of the DW hopping distance X_0 and the cross-sectional area A of the DW is key to reliably ascertain the β values using the analysis of the dwell times as a function of current. In contrast, the derived values of the current-field equivalence revealed similar values to previous experiments for the same material and given the fact that most parameters are reasonably well known, this method might prove more robust.

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FIG. 1: The time resolved extraordinary Hall voltage reveals two metastable states for a constant field (3.41 G) and a constant current $|\mathrm{I}| = 0.5\,\mathrm{mA}$ (inset) corresponding to a current density of $J = 1.16 \times 10^{11}$ A/m. The normalized cumulative distribution of both metastable states is fitted using the cumulative distribution function F(t) (solid lines).

FIG. 2: a) $\ln(\frac{\tau_1}{\tau_0})$ as a function of the applied field for constant currents. For each value of a current we determine the slope by a linear fit weighed with errors of the individual measurements. The values of a current are then refitted using their average slope. b) $\ln(\frac{\tau_1}{\tau_0})$ as a function of the injected current density for different constant fields. The non-adiabaticity factor β is calculated from average slope of all fits.