Spin-Transfer-Torque-Assisted Domain-Wall Creep in a Co/Pt Multilayer Wire

L. San Emeterio Alvarez,[1,*] K.-Y. Wang,[2,†] S. Lepadatu,[1] S. Landi,[3] S. J. Bending,[3] and C. H. Marrows[1,‡]
[1]*School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, United Kingdom*
[2]*Hitachi Cambridge Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom*
[3]*Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom*
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We have studied field- and current-driven domain-wall (DW) creep motion in a perpendicularly magnetized Co/Pt multilayer wire by real-time Kerr microscopy. The application of a dc current of density of $\lesssim 10^7$ A/cm^2 assisted only the DW creeping under field in the same direction as the electron flow, a signature of spin-transfer torque effects. We develop a model dealing with both bidirectional spin-transfer effects and Joule heating, with the same dynamical exponent $\mu = 1/4$ for both field- and current-driven creep, and use it to quantify the spin-transfer efficiency as 3.6 ± 0.6 Oe cm^2/MA in our wires, confirming the significant nonadiabatic contribution to the spin torque.

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It has become a commonplace that a high current density can cause the motion of a domain wall (DW) through the spin-transfer torque effect [1]. Research activity on the topic is currently very intensive, due to the prospect of its enabling the development of novel memory [2] and logic [3] architectures. Many recent studies of the phenomenon have made use of Permalloy nanowires [4,5], which are magnetized in plane. However, since the walls in these systems take on a variety of complex forms with internal degrees of freedom [6], they are not rigid when set in motion [7]. Simpler, narrower, Bloch-like walls are found in perpendicularly magnetized materials [8], the archetype for which is a multilayer of Co/Pt where the Co layer thickness $\lesssim 1$ nm.

While Co/Pt has previously been used to study DW magnetoresistance [9] and field-driven DW motion [10], only a few reports of DW spin-transfer torque experiments have so far appeared [11,12]. These include experiments where the Co/Pt multilayer is incorporated into a spin-valve demonstrating high spin-torque efficiency [13], or capped with AlO_x to induce a large Rashba spin-orbit interaction [14] yielding a large (so-called) nonadiabatic torque [15], meaning concomitantly large DW velocities can be achieved [16]. Spin-transfer studies in other perpendicularly magnetized metallic systems have also just been reported [17–20].

Here, we report on real-time imaging of the effects of high-density currents on creep-regime DW motion in Co/Pt multilayers. By a fortuitous combination of artificially formed and naturally occurring reverse domain nucleation sites, we are able to observe the motion of two DWs of opposite polarity in a single field of view, with the influence of a magnetic field causing them to creep in opposite directions. We were then able to simultaneously observe the effect of the spin-transfer torque on both walls under current: the DW creeping with the electron flow had a much higher creep velocity, while the DW creeping against it has only a very small change in its velocity. By developing a simple model that takes account of both the Joule heating and the bidirectional nature of the spin-transfer torque, we are able to reproduce this nonlinear behavior and quantify the large spin-transfer efficiency in our Co/Pt multilayer wires.

The sample studied was a sputtered multilayer of structure Pt(28 Å)/[Co(5 Å)/Pt(10 Å)]$_2$, with a quasistatic coercive field $H_c = 164$ Oe (Fig. 1). A hard-axis Kerr loop gives an effective anisotropy constant $K_{\mathrm{eff}} \approx 10^6$ J/m^3, yielding DWs of thickness $\Delta \sim 10$ nm. The multilayer was patterned into a 5 μm-wide Hall bar by electron beam lithography and liftoff. The magnetic properties of our material have previously been shown to be unaffected by this processing [21]. After patterning, a small area was irradiated in a focussed ion beam (FIB) system at a dose of 4.83×10^{12} Ga$^+$/cm^2, producing a site where a reverse domain can be controllably nucleated [21]. The magnetization configuration of the sample was observed in a polar Kerr effect microscope, illuminated by a Hg light source producing light in the wavelength range 300–700 nm. Imaging was carried out at room temperature, with a perpendicular field applied using an electromagnet. The Cr/Au contacts at either end of the bar were used to apply a dc current, while the voltage contacts were used to measure the wire resistance in order to perform thermometry.

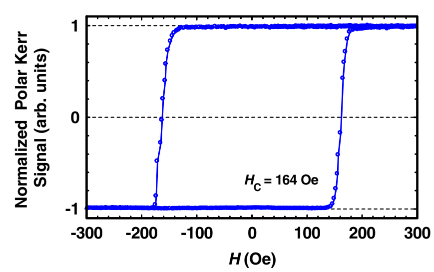

FIG. 1 (color online). Room-temperature polar Kerr effect hysteresis loop of an unpatterned Co/Pt multilayer.

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The measurement procedure was as follows: the device was first saturated by a large reverse field, confirmed by Kerr imaging. A small forward field was then applied to nucleate DWs. As well as a DW nucleating in the Ga^+-irradiated area (called DWC in Fig. 2), this also occurred at some defect, presumably arising from the lithography, at the third Hall cross in the wire (called DWB in Fig. 2). A slightly larger forward field, H, which is still less than H_c, was then applied. This caused these two walls, DWC and DWB, to move together towards the center of the wire. This propagation field H was kept constant during the subsequent imaging.

The measurements were done by recording real-time Kerr microscope movies for different fields and currents, from which snap-shots have been taken to determine the wall velocities. Some examples, recorded at $H = 136$ Oe, are shown in Fig. 2. At zero dc current [Fig. 2(a)], both walls move a distance of a few μm over an observation period of 180 s, giving velocities $\sim$10 nm/s. This low value, combined with the intermittent motion of the wall, and its irregular appearance, confirm that the motion of both walls is in the thermally activated creep regime [22].

The application of a dc current changes the behavior markedly. In Fig. 2(b), we show similar snapshots recorded while a current of $+3$ mA was flowing in the wire (current density $J = 9.84$ MA/cm^2 with electron flow from right to left). It can be seen that the motion of DWB is now significantly faster, the DW moving most of the length of the wire in a period of 300 s. Meanwhile, DWC still moves very slowly. The effects of an equal but opposite current are shown in Fig. 2(c). In this case, it is DWC that shows a significantly greater velocity. This asymmetry in wall velocity with current direction is the signature of the spin-transfer effect. We confirmed this result by carrying out the same experiment but with all field directions reversed: it is always the DW creeping in the direction of the electron flow whose motion is assisted.

By plotting the position of the DWs as a function of time and fitting the slope of the data, it is possible to obtain average velocities v for different values of H and J. A summary of the data we obtained is shown in Fig. 3. For $H \lesssim 120$ Oe, we observed no wall motion at any value of current density that would not excessively heat the wires, while for $H \gtrsim 150$ Oe, the wall motion was too rapid to record accurately with our 30 frame/s video capture rate, as H is too close to H_c. It is easy to see that the effect of increasing the current against the direction of wall motion is not very great. For DWB, there is a just discernible increase in wall velocity that we can assign to some Joule heating occurring, while the motion of DWC is

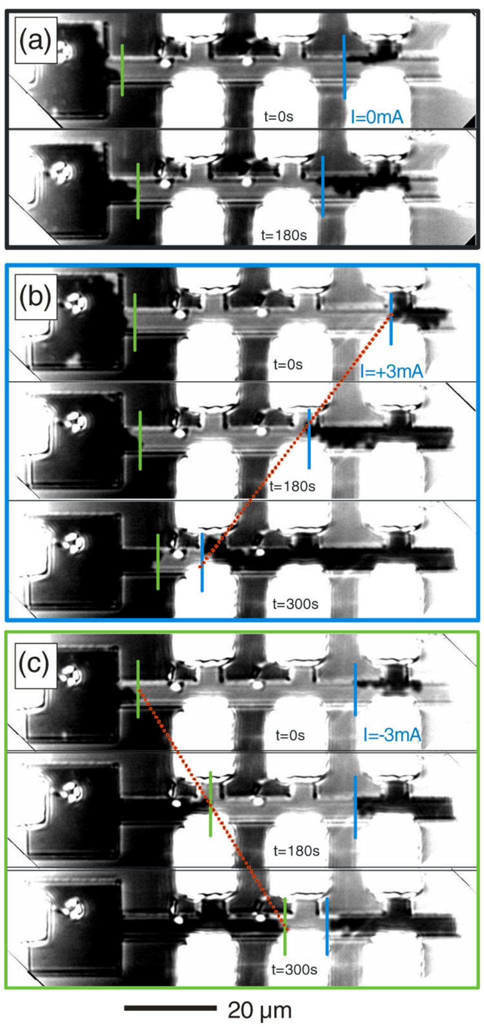

FIG. 2 (color online). Kerr microscope snapshots at different times of a device at constant field ($H = 136$ Oe). The positions of DWB and DWC are marked with vertical solid lines. Wall propagation is observed under no current (a), positive current of $+3$ mA (b), and negative current of -3 mA (c). The current-assisted creep motion is marked with a dotted line.

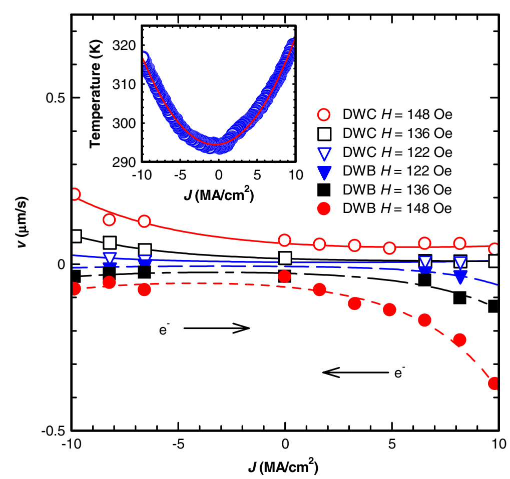

FIG. 3 (color online). Velocities of both DWs (DWC, open symbols; DWB, solid symbols) as a function of current density for fields of 122 Oe (▽, ▼), 136 Oe (□, ■), and 148 Oe (○, ●). The solid and dashed lines show the fits to the spin-transfer assisted creep model described by Eq. (2) in the text. The inset shows the wire temperature as a function of current density, with a solid line showing the quadratic fit.

actually slowed very slightly by the presence of the current. On the other hand, when the electron flow is in the same direction as the DW is creeping, we see a marked enhancement in velocity, far exceeding that due to the heating effect: the effect of the spin-transfer torque is to markedly speed up the creep motion: by a factor ~3 for DWC, and more than an order of magnitude for DWB, for a current density $\sim 10^7$ A/cm^2.

Field-driven creep motion can be described by the expression [23]

$$v(H) = v_0 \exp\left[-\left(\frac{H_c}{H}\right)^{\mu}\left(\frac{U_c}{k_B T}\right)\right], \qquad (1)$$

where H_c is the critical field below which the creep regime occurs, U_c is the pinning energy, v_0 is a velocity prefactor, k_B is the Boltzmann constant, T is the ambient temperature, and μ is a dynamic exponent, which is equal to 1/4 for an elastic 1-dimensional DW in a weakly disordered 2-dimensional medium [10], and previously shown to fit our materials [24]. To incorporate the effects of the current, we modify this expression to read

$$v(H, J) = v_0 \exp\left[-\left(\frac{H_c}{(H + \xi J)}\right)^{\mu}\left(\frac{U_c}{k_B(T + hJ^2)}\right)\right], \quad (2)$$

where we have inserted a rise in temperature due to Joule heating hJ^2 and the spin-transfer effect as an effective field ξJ (as was done in, e.g., Ref. [13]). Thus, we have assumed that $\mu = 1/4$ for current-driven creep as well as field-driven creep, as it is currently unknown in the former case for metallic systems such as these. (While it has been found that in GaMnAs $\mu = 0.33$ for spin-transfer-driven creep, field-driven creep in that material has $\mu = 1.2$ [25], and so the creep dynamics are not the same, and we cannot apply that value to the present case.) We would argue that treating the spin-transfer as an effective field can be justified in Co/Pt due to the the large nonadiabatic contribution to the torque [12], which has a fieldlike symmetry [26]. Indeed, Miron *et al.* have shown that field and current are directly interconvertible in a closely related materials system [15]. Provided that $\xi J > -H$, our model has the useful property that it can treat the effect on the wall motion of current densities of either sense.

We have experimentally determined the Joule heating effect by measuring the wire resistance under ambient conditions as a function of current density, and then converting this resistance into a temperature using the temperature coefficient of resistance (0.093 ± 0.009 Ω/K), measured by placing the chip on a temperature controlled hotplate and measuring the resistance rise for various temperatures up to ~323 K. The result is shown in the inset of Fig. 3: the temperature rise at the highest current density is ~20 K above ambient. The data are fitted well by a quadratic, yielding $h = 0.25 \pm 0.02$ K/(MA/cm^2)^2.

We plot the velocity data as a function of J in Fig. 3 for three values of field, $H = 122$, 136, and 148 Oe, along with the fits to Eq. (2) using the above value for h and $T = 294$ K. Good quality fits to all six sets of data shown have been achieved. By assuming that $H_c = 164$ Oe, the quasi-static coercivity, we may obtain $U_c = 0.30 \pm 0.03$ eV from all six fits, where the error bar is the standard error of the distribution of the six values. We hence determine the spin-torque efficiency $\xi = 3.6 \pm 0.6$ Oe cm^2/MA from these fits on the same way.

Our value of ξ is markedly higher than that in Permalloy, where a value of ~0.05 Oe cm^2/MA was found by Vernier *et al.* [4]. It is in closer agreement with the value of 8 Oe cm^2/MA found by Miron *et al.* using a spin-transfer torquemeter, for AlO_x-capped Co/Pt [15], and matches well with the 2.5 Oe cm^2/MA measured by Boulle *et al.* [12] by depinning experiments in a Co/Pt wire. It is within an order of magnitude of the estimate of ~23 Oe cm^2/MA found by Ravelosona *et al.* by depinning measurements in their Co/Pt-based spin valve (the complex structure of which makes the exact calculation of the relevant current density difficult) [13]. None of these experiments dealt with long-distance creep, averaged over a large number of pinning sites as we have done.

We can estimate the nonadiabaticity parameter by the same means as Boulle *et al.* [12] with the formula $\beta = 2eM_s\Delta\mu_0\xi/P\hbar\pi$ (obtained by equating the Landau-Lifschitz and nonadiabatic torques in the formalism of Thiaville *et al.* [26]). To do so, we estimate the diffusive spin-polarization [27] of the current $P = (\alpha - 1)/(\alpha + 1) \approx 0.7$ by using the measured value of $\alpha = \sigma_\uparrow/\sigma_\downarrow = 5.5$ obtained from DW resistance measurements in our materials [9]. Combined with the magnetization $M_s = 1.4 \times 10^6$ A/m for Co, this yields a value of $\beta = 0.7 \pm 0.1$: in line with the large values, of order unity, that have previously been found under other experimental conditions in Co/Pt-based systems [12,15]. We note that, strictly, this is an upper limit, as some small part of the torque may be adiabatic. Detailed micromagnetic calculations of the way that torques of different symmetry affect individual depinning events will be needed to resolve this point rigorously.

To summarize, we have observed long-distance DW creep-motion, and its modification by high current densities, in a Co/Pt multilayer by Kerr microscopy. The asymmetry of the effect of the current confirms that spin-transfer is the relevant mechanism, and we have confirmed that the significantly enhanced values of the spin-torque efficiency found previously for Co/Pt also apply in this regime of motion, indicating a value of $\beta \approx 1$. Like Boulle *et al.* [12], we observed the effects of spin-transfer torque only in a narrow range of field values just below H_c, due to the strong pinning present in these films. The effect of the current is highly nonlinear, due to the nature of the scaling of DW velocity with driving forces in the creep regime: we only observe a significant effect when the spin-polarized electron flow matches the field-driven creep motion. This diodelike behavior may be useful for control of DWs in nanotechnologies based on such materials. In the future, a reduction of the strength or number of pinning sites should make it possible to move DWs with spin-transfer torque alone in a perpendicularly magnetized system using the very large nonadiabatic torques that are available. One route to this goal is the use of amorphous ferromagnets [28] although Oersted field effects dominated at the high J response in a recent experiment on this type of material [29]. Another method tried recently is the use of He^{+} ion irradiation although the reduction in Curie temperature obscured any spin-transfer effects at high J [22]. These two early results notwithstanding, a suitable choice of material and processing route could yet yield current-controlled DW motion at low current density in a related system.

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*Present Address: Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom.
†Present Address: SKLSM, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China.
‡c.h.marrows@leeds.ac.uk

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