

Direct Observation of Domain-Wall Configurations Transformed by Spin Currents

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(Received 15 November 2004; revised manuscript received 15 April 2005; published 8 July 2005)

Direct observations of current-induced domain-wall propagation by spin-polarized scanning electron microscopy are reported. Current pulses move head-to-head as well as tail-to-tail walls in submicrometer $\text{Fe}_{20}\text{Ni}_{80}$ wires in the direction of the electron flow, and a decay of the wall velocity with the number of injected current pulses is observed. High-resolution images of the domain walls reveal that the wall spin structure is transformed from a vortex to a transverse configuration with subsequent pulse injections. The change in spin structure is directly correlated with the decay of the velocity.

DOI: [10.1103/PhysRevLett.95.026601](https://doi.org/10.1103/PhysRevLett.95.026601)

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

New approaches to the switching of magnetic nanostructures are currently being investigated intensively because easy and reproducible switching is critical to the use of any spintronic device. Beyond conventional switching by magnetic fields, a promising approach is current-induced magnetization switching, which was shown to be able to reverse the soft layer of a giant-magnetoresistive multilayer structure [1]. As recently demonstrated, spin-transfer effects can also be used to displace a magnetic domain wall by injecting current [2–7]. This effect shows potential for novel memory and logic devices based on domain-wall propagation [8] as it could simplify designs by eliminating magnetic field-generating circuits. While field-induced domain-wall motion is well established, current-induced domain-wall motion is still not thoroughly understood. Several effects occur when large electrical currents flow across a domain wall, the most prominent ones being the action of the field created by the current itself (the so-called Oersted field) and the spin momentum transfer, also known as the spin-torque effect [9]. Domain drag is believed to be important only in thick films [10], and linear momentum transfer only at high frequencies or for very narrow domain walls [11,12].

The understanding of the spin-torque effect has been extended recently by various approaches that treat the interactions between the spin current and the magnetization, but the appropriate form of the spin-transfer contribution still is the subject of much debate. Most theoretical models describing the current interaction with wide domain walls are based on the adiabatic approximation, in which the spin polarization of the current is assumed to remain aligned with the magnetization vector in the domain wall [12–16]. These models explain current-induced wall motion qualitatively, but only for currents much larger than observed experimentally [14,15]. Corrections to the adiabatic approximation have been introduced [17–19], with an additional nonadiabatic term related to the spatial mistracking of spins between conduction electrons and

local magnetization. While some of these approaches predict a wall motion at reduced current density [19] and some find wall velocities of the order of magnitude observed experimentally [17], the parameters and the results of the calculations vary significantly. Interestingly, all theories predict that the spin current modifies the wall structure, but they disagree on whether this change is transient or permanent, and whether it is a subtle distortion or even a change of wall type. Thus observing domain-wall spin-structure changes is expected to provide important input to refine current theories.

Experimentally, the domain-wall displacement, the velocities, and the critical current densities have recently been measured in various single-layer geometries [3–6] and in multilayer wires [2]. Interestingly, it was found that the walls do not always move with constant velocity or even stop moving [5,7]. This has been attributed mainly to extrinsic mechanisms, such as materials degradation or pinning. Alternatively, it has been suggested that an intrinsic magnetic effect, such as a change in spin structure, could play a role [7]. To our knowledge, experiments to test this conjecture have not yet been done.

In this Letter we report current-induced domain-wall displacement experiments that are combined with *in situ* high-resolution magnetic imaging. Effects of current pulses on head-to-head domain walls in straight submicrometer $\text{Fe}_{20}\text{Ni}_{80}$ (Permalloy) wires are imaged using spin-polarized scanning electron microscopy (spin-SEM or SEMPA). Variations of the domain-wall velocity with the number of current-pulse injections at a constant current density are compared and correlated with modifications of the nanoscale domain-wall configuration induced by the current.

We investigate $\text{Fe}_{20}\text{Ni}_{80}$ wires with a zigzag geometry; see Fig. 1(a). Straight wire segments 20 μm long are connected by bends that consist of 45° ring sections having a radius of 2 μm . We have fabricated wires with widths ranging from 100 to 500 nm and thicknesses from 6 to

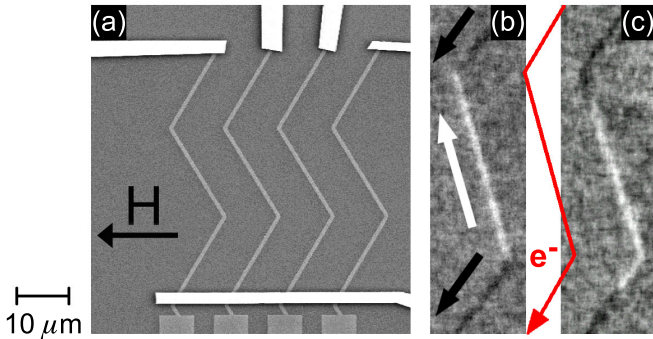


FIG. 1 (color online). (a) Topographic image of the device structure showing the Au contacts (white) and the four zigzag $\text{Fe}_{20}\text{Ni}_{80}$ wires (light gray) with square pads at the bottom. (b) Magnetization configuration in a wire after magnetizing with a field pulse along the direction indicated by the arrow. White (black) corresponds to the magnetization pointing up (down) within the plane; a head-to-head wall is formed at the top bend, a tail-to-tail wall at the bottom. (c) After injection of a single $10 \mu\text{s}$ long current pulse through this wire, both domain walls have moved in the direction of the electron flow as indicated by the arrow.

27 nm on a Si substrate covered by native oxide using electron-beam lithography and a two-step lift-off process as described in Ref. [20]. $\text{Fe}_{20}\text{Ni}_{80}$ was deposited by molecular beam epitaxy at $\sim 5 \times 10^{-10}$ mbar, followed by a thin 1.5 nm Fe layer, a 2 nm Au capping layer to prevent oxidation, and subsequent lift-off. The Fe layer enhances the magnetic contrast during imaging without altering the magnetic properties significantly. Finally, 100 nm thick sputtered Au contacts are defined in a second lithography step to contact each wire individually.

The current injection experiments and magnetic imaging of both in-plane magnetization components were performed in our spin-SEM setup [21]. Topography and magnetization distribution are determined simultaneously and with a lateral resolution of ≈ 20 nm. Prior to imaging, the Au capping layer was removed by mild Ne^+ ion bombardment.

The zigzag geometry is chosen as it allows the magnetic configuration of the wires to be controlled by application of an external magnetic field. After saturation along the direction indicated in Fig. 1(a) and relaxation of the field to zero, shape anisotropy forces the magnetization to form domains of alternating directions in adjacent segments; see Fig. 1(b). At the bends head-to-head and tail-to-tail walls form [22]. The dimensions of the wire control the type of the domain walls [23,24]. In this Letter we concentrate on 500 nm wide and 10 nm thick wires that result in vortex walls.

After initializing the system with a magnetic field ≥ 60 kA/m, a head-to-head domain wall is located at the upper bend and a tail-to-tail wall at the lower bend. Then a single current pulse of $10 \mu\text{s}$ duration is injected with a current density of 2.2×10^{12} A/m². This current density is 10% higher than the threshold current density at which

domain-wall motion sets in, which was measured to be the same for walls located at a bend or in the straight part of the wire within an accuracy of 10%. After injection, both walls have moved in the direction of the electron flow; see Fig. 1(c). The distances the head-to-head and tail-to-tail walls have traveled are 3.0 and 2.9 μm , respectively, which yields a mean wall velocity of 0.3 m/s for the $10 \mu\text{s}$ pulse. As both walls propagate in the same direction, the Oersted field can be excluded as a possible cause for wall motion: Our observation is consistent with an explanation based on the spin-torque effect due to the current pulse. Correspondingly, injecting a current pulse with opposite polarity moves both walls back to the bends.

To exclude effects related to the curved geometry at the bend, we consider in the following wall propagation in the straight part of the wire, i.e., where the wall is located after the first current-pulse injection. Starting from this configuration, current pulses ($10 \mu\text{s}$ duration with current density 2.2×10^{12} A/m²) are injected and the domain wall velocity for each pulse is determined. Figure 2 shows the evolution of the velocity with the number of injected current pulses for three different walls. After initialization, the walls propagate under pulse injection. After a few injections, however, the walls stop moving. The starting velocity can be retrieved by reinitializing the sample with a magnetic field as described above, which was carried out before injections 11 and 26. The complete stopping of the walls was a general observation for all walls in our straight wire segments. The number of injections after which the wall stops moving varies from a few to a few tens. We note that wall motion in general is a stochastic process, and nonconstant wall velocities have also been observed in other experiments [5,7].

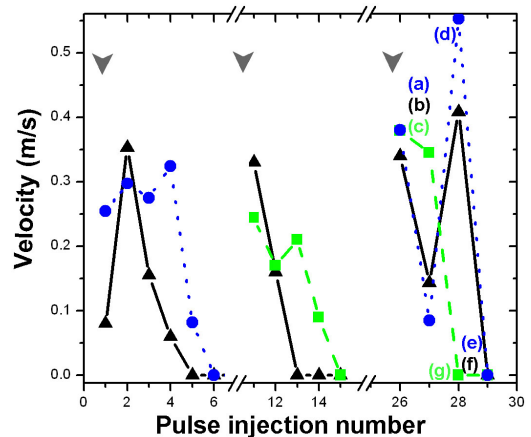


FIG. 2 (color online). Domain-wall velocity as a function of pulse injection number determined from spin-SEM images (wall α : blue circles, dotted line; β : black triangles, solid line; γ : green squares, dashed line). The magnetic state has been reinitialized by a magnetic field before pulses 1, 11, and 26, as indicated by the arrows. After pulses 26 to 28, high-resolution images of the domain wall have been taken. The labels are related to the images shown in Fig. 3. Statistical uncertainty of the wall velocity is 0.05 m/s.

To understand the wall-velocity decay, we have taken high-resolution images of the spin structure of three domain walls (labeled α , β , γ) after subsequent injections (26 to 29), as shown in Fig. 3. The first pulse (injection 26) moves the domain walls into the straight part of the wire, similar to Fig. 1(c). All three walls are vortex walls with a well centered core and a width w ranging from 400 to 660 nm, as determined from a fit with the usual $\tanh(x/w)$ function [Figs. 3(a)–3(c)]. A micromagnetic simulation of a relaxed vortex wall in a perfect wire reproduce this spin structure with $w = 400$ nm. The next injection modifies the structure of wall α [Fig. 3(d)]: While the wall still contains a vortex core, it has acquired a transverse component. The subsequent injection, 28, drastically changes the structure of the wall [Fig. 3(e)]: The vortex is eliminated, and a narrow (210 nm) distorted transverse wall has formed. Further injections do not move the wall anymore.

The other two walls display the same behavior: Wall β , starting from a vortex [Fig. 3(b)], has attained a transverse structure after injection 28 that is very similar to that of wall α [Fig. 3(f)]. Likewise, it does not move anymore with subsequent injections. Wall γ already fails to move after injection 27. Again, the wall has a strongly distorted transverse character, with the vortex core annihilated or expelled from the structure [Fig. 3(g)].

Thus, in all three cases the walls move as long as they are vortex walls but stop moving when they attain a transverse structure. From these observations we conclude that a direct correlation between the spin structure and the domain-wall velocity exists, which we propose to be the cause for the behavior of the wall velocity observed in our experiments as well as that of others [5,7].

Defects cannot directly account for the domain walls stopping after a few injections: The walls have been moved by the current pulses over the entire area between the

bends, and have even passed the position at which they eventually stop a number of times. Moreover, after every reinitialization and current injection, the walls stop at a different position of the wire. High-resolution imaging of the different wire sections at which the walls stop does not reveal any obvious structural defects that might lead to pinning. We can also exclude structural damage to the material due to the high current densities as a cause for the wall stopping. As seen in Fig. 2, the wall velocity starts with similar values after each reinitialization. In addition, the resistance of the wires stayed constant at 5 k Ω over the course of the experiment, which means that no detrimental effects such as electromigration or excessive heating were discernible. Hence we conclude that the electrical current induces both motion and distortion of the wall.

Recent theories qualitatively predict some domain-wall distortion induced by the spin current [14,17–19]. For a 1D Néel wall, Li and Zhang predict a transient distortion which builds up during the first few nanoseconds [14]. Waintal and Viret [18] anticipate significant distortions of the wall structure up to the point at which the wall switches between different types. A step beyond the 1D models has been taken by Thiaville *et al.* [19] with a 2D micromagnetic simulation. For a wire narrower than ours they find a periodic transformation of the wall structure from vortex to transverse, albeit at larger current densities.

While the domain-wall motion is caused by the spin torque, the origin of the wall transformation is less obvious. The most prominent signature of our observation is the breaking of the wall symmetry. *A priori*, spin torque alone is not necessarily very effective in achieving this. Only at current densities much larger than our experimental value do Thiaville *et al.* report such a transformation of wall types [19]. The Lorentz force also breaks the symmetry. It leads to domain drag in thick films [10]. In our thin films, it

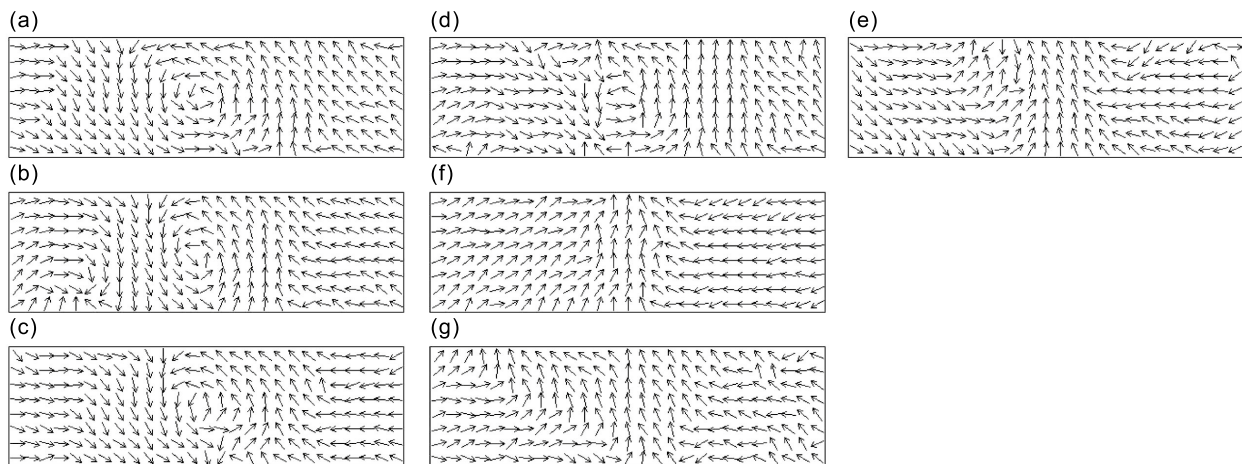


FIG. 3. High-resolution experimental images of the spin structure of domain walls (a),(d),(e) α , (b),(f) β , and (c),(g) γ . After the first current injection 26, the walls are all of vortex type (a),(b),(c). After injection 27, wall γ has stopped moving and undergone a drastic transformation to a very distorted transverse wall type (g), whereas the mobile wall α has a vortex core and a large transverse component (d). After injection 28, walls α and β have also stopped and changed to transverse walls (e),(f). The arrow images are constructed from the two orthogonal in-plane magnetization components taken by spin-SEM. Image size: 1600 nm by 500 nm.

is not the dominant effect for domain-wall propagation, but it exerts a transverse force on the perpendicularly magnetized vortex core. This could help pushing it off the center and eventually expel it from the wire. Thus, while domain-wall spin-structure modifications and even transitions from vortex to transverse walls due to spin currents have been predicted, other intrinsic magnetic effects could play a role. Calculations have to be carried out for our geometry to discriminate between the possible explanations and gain a deeper understanding of our observations.

Further to the observation of domain-wall transformation, our experiments demonstrate a direct correlation between the change of wall structure and the reduction of wall velocity. Additional measurements on wires with different dimensions show that the velocity after field initialization also depends on the wire width and thickness and hence on the wall width for constant current density: The velocity is 0.3 m/s for a width of 500 nm and thickness of 10 nm, but 1.2 m/s for a width of 200 nm and thickness of 27 nm. A detailed systematic study is beyond the scope of this Letter and will be published elsewhere.

Our observations of varying velocities are in striking disagreement with theoretical models [13,17,19], which predict the velocities to be dependent only on material parameters and on the current density, but not on the type of the wall and its spin structure. Moreover, our experimental mean velocities are smaller than those calculated by at least 1 order of magnitude [15,17,19].

These discrepancies between experiment and calculation are unresolved. We feel that thermal excitations may play a significant role. At finite temperature, spin waves reduce the spin polarization of the current that exerts the spin torque on the wall [25]. Further theoretical work is needed to quantum mechanically calculate the consequences for the spin wave dispersion, but also to include finite temperature effects in micromagnetic simulations.

In conclusion, we have observed current-induced domain-wall propagation by spin-polarized scanning electron microscopy. Head-to-head as well as tail-to-tail domain walls in 500 nm wide and 10 nm thick $\text{Fe}_{20}\text{Ni}_{80}$ wires both move in the direction of the electron flow with a mean velocity of 0.3 m/s, which is consistent with an explanation based on the spin-torque effect. The velocity varies, and after a number of pulse injections the walls eventually stop moving. The original velocity is reestablished by reinitializing the sample with a magnetic field. High-resolution images of the wall structure after consecutive pulse injections show a transformation from a vortex wall to a distorted transverse wall due to the current. The change in wall velocity is correlated with a change in the domain-wall spin structure. These results are largely not reproduced using the theoretical models currently available. Our observation of a drastic change in wall structure by current is a salient feature, which should stimulate further development of theory and lead to a deeper insight into the interactions between current and magnetic domain walls.

This work was partially funded by the CMI Magnetoelectronic Devices project and the “Deutsche Forschungsgemeinschaft” (SFB 513). M. K. acknowledges the “Deutscher Akademischer Austauschdienst” (DAAD) for financial support.

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