Control of Domain Wall Polarity by Current Pulses

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Direct observation of current-induced propagation of purely transverse magnetic domain walls with spin-polarized scanning electron microscopy is reported in $Fe_{30}Ni_{70}$ nanowires. After propagation, the domain walls keep their transverse nature but switch polarity in some cases. For uniform $Ni_{70}Fe_{30}$ wires, the effect is random and illustrates domain-wall propagation above the Walker threshold. In the case of $Ni_{70}Fe_{30}$/Fe wires, the transverse magnetization component in the wall is entirely determined by the polarity of the current pulse, an effect that is not reconciled by present theories even when taking into account the nonuniform Oersted field generated by the current.

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Propagation of a magnetic domain wall (DW) in a nanowire with spin-polarized current is critical for the development of magnetic memory and logic elements [1,2]. The effects of the current are generally explained by the transfer of spin angular momentum from the conduction electrons to the magnetization as the electrons traverse the domain- wall [3,4]. Recent time-resolved measurements [5,6] demonstrate that this 1D model based on the Malozemoff-Slonczewski formalism [7–9] captures the essence of the underlying physics. In nanowires of soft magnetic materials, two basic types of domain walls exist, vortex and transverse DWs, which differ in their 2D structure. Vortex DWs, in which the magnetization rotates within the plane around a perpendicular core, are studied more often because they are encountered in nanowires of large dimension. Transverse DWs, which can be described as triangular areas of uniform transverse magnetization with 90° domain walls on both sides, are experimentally more challenging.

It has been reported that vortex DWs can be moved [10] and transformed [11–13] by electrical current pulses. For some wire geometries, both vortex and metastable transverse DWs can be observed [14]. Current-induced transformation of a DW pinned in a constriction from one state to the other is possible [13] by nucleation or annihilation of a magnetic vortex. Field-assisted transverse wall propagation [15] and field-assisted transformation through an antivortex state [16] have been detected, but propagation of purely transverse walls by current alone remains elusive, and no experimental confirmation has so far been provided [1].

Transverse DWs could become critical for practical applications because they are the stable form in the very narrow wires required to achieve high-density information storage. Also, in contrast to vortex DWs, they exhibit an in-plane stray field which could be useful for real-time detection of the wall position, an important requirement for the readout scheme of any DW-based device [1,2].

In this Letter we report on current-induced propagation of stable transverse DWs in two type of wires: uniform NiFe and asymmetric NiFe/Fe bilayers. In the latter case, we discovered a new effect: the transverse DW polarity—defined as the direction of the wall's transverse magnetization—is set by the current.

The experiments were done in magnetic nanowires with zigzag geometry [11]. Their width, 150 nm, was kept small to ensure that the equilibrium domain wall in these structures is of transverse type [17]. The wires were fabricated by electron-beam lithography and lift-off: On a Si wafer terminated by 6 nm thermal Si oxide, a bilayer composed of 8 nm $Ni_{70}Fe_{30}$ and 2 nm Fe was grown by electron-beam evaporation, covered by a 2 nm Pt protecting layer to prevent oxidation. Each sample consisted of four parallel wires, contacted by separate electrodes at both ends. Prior to the experiment, the Pt top layer was removed by *in situ* mild Ne^+ ion bombardment controlled by Auger electron spectroscopy. Two series of experiments were performed, first on the bilayer NiFe/Fe wires and then on the bare NiFe wires after removal of the top Fe layer.

Domain walls were created at the bends of the wires by applying a large in-plane magnetic field perpendicularly to the overall direction of the wires [18]. The polarity of this field also set the initial transverse wall polarity. We injected current pulses of microsecond duration with a current density of up to 1.9×10^{12} A/m^2 and a rise time of 0.4 μs. The resulting change in the nanowire resistance was measured, and by comparing it with the resistance change in a NiFe film upon annealing [19,20], we infer that the temperature rise due to Joule heating is <250 K.

The magnetization state of these structures and, in particular, the DW configurations were imaged before and after injection of current pulses with our spin-polarized scanning electron microscope (spin-SEM) setup [21]. Both in-plane magnetization components were measured so as to determine not only the position of the domain wall but also its internal structure, in particular, the polarity of the transverse wall.

Figure 1 proves that a transverse wall moves upon injection of a current pulse without the support of an additional magnetic field. It retains all its characteristics of an equilibrium wall in a nanowire of these dimensions. Wall propagation is consistent with the spin-transfer torque

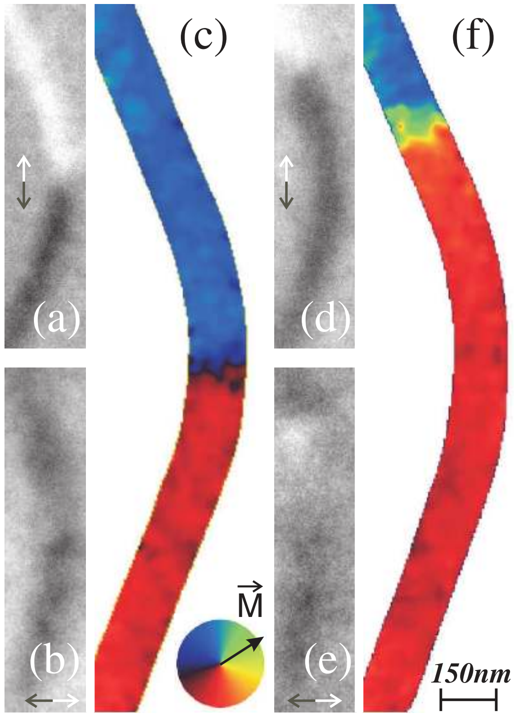

FIG. 1 (color). Transverse tail-to-tail domain-wall in a 150 nm-wide $Fe_{30}Ni_{70}/Fe$ bilayer wire before (a)–(c) and after (d)–(f) injection of a current pulse. (a),(b) and (d),(e) In-plane magnetization components along the indicated axis. (c) Color representation of the in-plane magnetization, constructed from the two orthogonal magnetization components shown in (a) and (b), with the in-plane magnetization angle coded according to the color wheel. (f) Color representation constructed from (d) and (e) of the same wall displaced upwards by ~600 nm after injection of a 2-μs-long current pulse with a current density of 1.5×10^{12} A/m^2. The electron flow direction was from bottom to top; the wall polarity has reversed.

effect, with the DW propagating in the direction of the electron flow. The current density is 1.5×10^{12} A/m^2, comparable with values observed for vortex-wall propagation [10–12]. It is somewhat larger than the critical current, 1.2×10^{12} A/m^2, which we measured for vortex DWs in 550-nm-wide wires of the same thickness. The critical current is observed to be the same for the NiFe and the NiFe/Fe wires.

For our typical pulse duration of 2 μs, we observe a stochastic propagation, similar to the findings for vortex walls [11,22], without identifiable structural defects in the wires. The average DW velocity, calculated as the ratio of the distance of propagation to the duration of the current pulse, ranges from 0.06 to 2 m/s. These velocities are consistently smaller than those observed in experiments in which vortex-wall propagation was triggered by a magnetic field pulse [5,23].

In recent experiments [23], transverse DWs could not be moved by a current pulse. We attribute this different behavior to the fact that these wires were wider (200 nm), so that transverse walls could only be created as metastable objects by large nucleation fields, whereas for our wires a transverse DW is the lowest energy state.

Figure 1 displays the in-plane magnetization in the NiFe/Fe wires before and after propagation. The initial wall polarity is set by the transverse magnetic field pulse, pointing to the left in Fig. 1. Upon current pulse injection, the DW propagated by ~600 nm, accompanied by a switch of the wall polarity: The transverse magnetization now points to the right, Fig. 1(f), with the characteristic triangular shape as modeled by micromagnetic simulations for an equilibrium transverse DW.

Strikingly, the results are completely different for the two types of wire. In the case of the uniform NiFe wires, we observed that the DW's polarity switches in a random manner after a current pulse. In the present theories of current-induced DW dynamics, two regimes are distinguished [3,9]: At low current density j, the wall propagates and keeps its structure without change. At higher currents, above the Walker breakdown [8], the average wall velocity is reduced, and the wall structure transforms periodically on a time scale of nanoseconds, similarly to what was reported for magnetic-field-induced propagation [16]. It appears that because of the high pinning field of the transverse DW, propagation only occurs in the regime of DW transformation. As our current pulse is 2 orders of magnitude longer than the switching period, the final polarity of the DW has a 50% probability to be found in one of the two states, which explains our results.

The presence of the Fe overlayer completely changes the results in an unexpected way. Figure 2 illustrates the effect for head-to-head and tail-to-tail domain walls on the same NiFe/Fe wire. Initially the transverse components point to the left (dark contrast, red arrows). After a first current injection, with electrons flowing to the top, the transverse components are reversed to the right (bright contrast, blue arrows). A subsequent current pulse of opposite direction (electrons flowing to the bottom) reverses the wall polarity to its initial state. More than 20 propagation events have been recorded, proving that the underlying phenomenon is not a random switching of the wall polarity The final wall polarity is independent of the initial polarity, the propagation distance, and the tail-to-tail or head-to-head nature of the walls. Variation of the current density from 1.5×10^{12} to 1.9×10^{12} A/m^2 and of the pulse duration (1–2 μs) also did not modify the result. However, the wall polarity remains unchanged when the domain walls do not move upon current injection. The polarity reversal occurred in both the straight section of the nanowire and the bends without measurable difference, indicating that the nanowire curvature does not play a role in the effect reported. For walls whose polarity already pointed along the direction into which the current pulse will set it, propagation occurred without polarity change. Clearly, the symmetry between the two wall polarities is not preserved for the bilayer, contrary to the case of uniform NiFe wires.

The observed wall polarity reversal is a key finding of our experiments: It is entirely controlled by the direction of

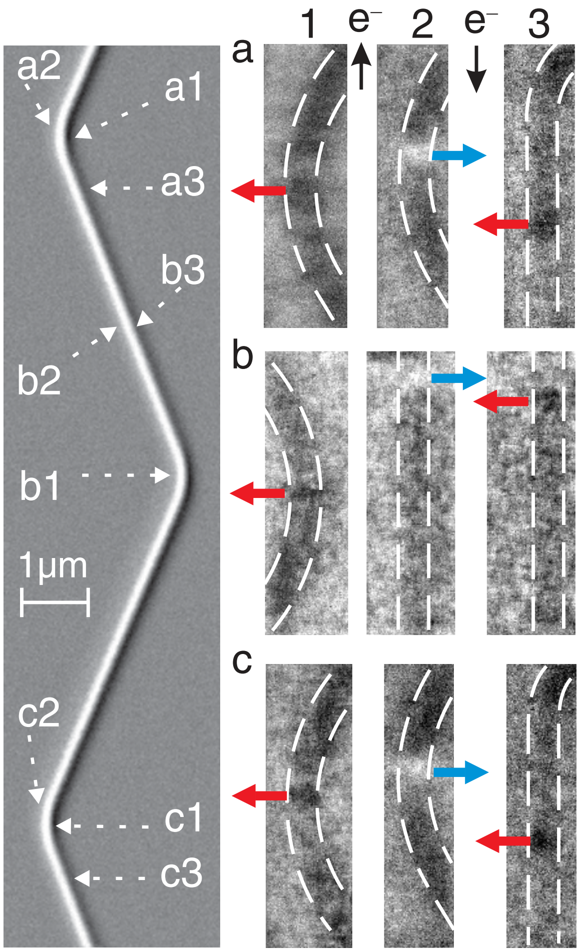

FIG. 2 (color online). Current-induced switching of the polarity of transverse domain walls as observed by spin-SEM. The in-plane magnetization component perpendicular to the long wire axis is shown for head-to-head (a),(c) and tail-to-tail (b) walls in the same wire. After field-induced creation, the wall polarity points to the left (dark contrast, red arrows). After a current pulse with electrons flowing to the top, the wall polarity switches to the right (bright contrast, blue arrows). After a further opposite current pulse, the walls switch their polarity again. For each image, the location of the wall is indicated in the overview topography image. Current density is 1.8×10^{12} A/m^2. The boundaries of the 150 nm-wide wires are indicated as dashed lines.

the current injection, and it is fully reproducible. This is the first demonstration of a current-induced controllable setting of a freestanding domain-wall configuration. In contrast to previous results on current-induced transformation of domain walls [11,13], the observed phenomenon is reversible and does not modify the domain-wall type.

We now discuss the controllable setting of the wall polarity with a full 3D micromagnetic simulation based on spin-transfer torque. The criterium we used to quantify the symmetry breaking was to evolve transverse DWs with both polarities above the Walker threshold and to compare the polarity reversal times. These simulations were conducted with the OOMMF code [24], modified so as to include the two spin-torque terms induced by the current [9]. We used the following micromagnetic parameters: exchange stiffness $A_{\rm NiFe} = 13 \times 10^{-12}$ J/m, $A_{\rm Fe} = 21 \times 10^{-12}$ J/m, magnetization M_s(NiFe) = 730 kA/m, M_s(Fe) = 1600 kA/m, damping constant $\alpha = 0.01$, and a vanishing magnetic anisotropy. A relatively large value for the nonadiabatic spin-torque parameter, $\beta = 0.15$, was needed to reach the DW transformation regime. The exchange at the interface between NiFe and Fe was assumed to be equal to the NiFe exchange. The simulation cell size was $5 \times 5 \times 2$ nm^3. The important parameter for the spin-torque terms is $u \propto jP/M_s$, with P the spin polarization of the current. As the precise P is still debated, we check in different simulations that modifying the relative value of u in the Fe and NiFe layers by a factor of 4 does not introduce any noticeable breaking of the symmetry. We hence use a uniform u in the wire based on a measured $P = 34\%$ in NiFe [25].

The Oersted field could play an important role, considering the high current density involved. In our wire geometry, a current of 2×10^{12} A/m^2 generates maximum transverse fields close to 8 kA. We calculated the Oersted field for the simulations, considering that Fe was measured to be 50% more resistive than NiFe in continuous films.

Figure 3 presents the transformation of the DW for the uniform NiFe and the asymmetric NiFe/Fe wires. The route from one polarity to the opposite one was always found to proceed through the nucleation of an antivortex [26,27] at one side of the wire and its lateral propagation toward the opposite side where it is annihilated, as illustrated in Fig. 3(a). Variation of the energy of the DWs is shown in Fig. 3(b): as the wall transforms, the energy increases, reaching a maximum for the antivortex state. Then it decreases again, arriving at the energy minimum corresponding to the opposite wall polarity. For the uniform NiFe wire, we verified that both polarities are energetically exactly equivalent. For the bilayer case, because of the higher resistivity and higher magnetization in Fe, the Oersted field favors DWs whose transverse component points left considering the flow of electrons. This completely contradicts the observed transformations shown in Fig. 2.

We conclude that the observed effect cannot be accounted for by present theories. The energy difference between the two states, 6×10^{-19} J, is huge compared with the thermal energy at the temperature reached during the pulse: $k_B T = k_B \times 500$ K $= 7 \times 10^{-21}$ J. On the other hand, it is about a factor of 4 smaller than the barrier imposed by the intermediate antivortex state. Hence it is impossible that thermal instabilities could transform a domain from one polarity to the opposite. This is also supported by our observation that pinned, nonmoving domain walls never changed polarity after a pulse injection.

In summary, we investigated current-induced propagation and transformation of purely transverse domain walls in magnetic nanowires. Current-induced propagation of

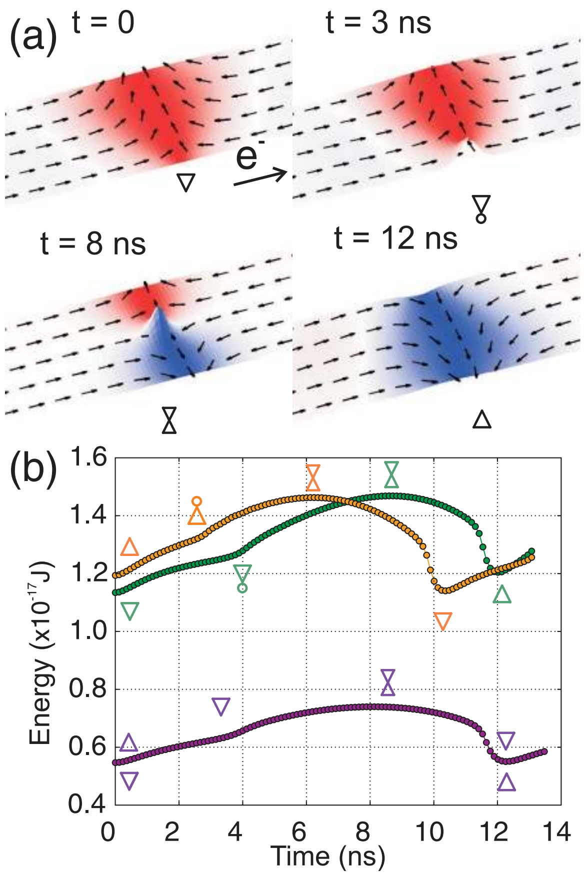

FIG. 3 (color). Micromagnetic simulations for infinitely long 150-nm-wide wires of composition NiFe(8 nm) and NiFe(8 nm)/Fe(2 nm), considering that the electrical resistivity of the Fe layer is 50% larger than that of the NiFe layer; polarized current parameter $u = 50$ m/s. (a) Transformation of the transverse domain-wall structure in a uniform NiFe wire during the propagation, with electrons flowing to the right; the in-plane transverse magnetization component is color-coded (blue to red), the out-of-plane component is represented as the height. (b) Wall energy versus time in a NiFe(8 nm)/Fe(2 nm) wire for both initial wall polarities (orange and green) and in uniform NiFe(8 nm) (purple).

transverse domain walls was demonstrated with slightly higher critical current than for vortex walls, without assistance of a magnetic field. In bilayer wires, we found a new effect: The current direction controls and sets the polarity of the transverse wall. We showed that the Oersted field can be excluded as the cause for this effect because it favors setting the opposite polarity.

The perfect reproducibility of the observed phenomenon implies that the commonly used theoretical model of current-induced domain-wall propagation is incomplete. In particular, the importance of frequent pinning or depinning events during a microsecond pulse at random wire imperfections is entirely neglected, but was demonstrated to be important already for field-driven wall motion [26]. Moreover, we suggest that a more rigorous treatment of thermal effects is required [28] to prove that the calculated energy barriers properly describe the phenomenon.

It now seems feasible to exploit the asymmetric nature of bilayers for future device architectures. One could envisage, for instance, wires with sections supporting wall polarity reversals, or domain-wall diodes based on a constriction at which one polarity is blocked and the opposite one can pass freely.

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