Spin-current-induced magnetization reversal in magnetic nanowires with constrictions

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We have performed experiments on current-induced domain-wall motion (CIDWM) in the case of the domain walls (DW) trapped within the nanoscale constrictions in patterned NiFe structures. Direct observation of current-induced magnetization reversal was achieved and critical current densities j_c were measured in the presence of easy-axis magnetic fields. The direction of CIDWM was found to be along the direction of the electron motion in absence of an applied magnetic field and in the direction of the field when in the presence of even relatively weak fields. Data for the field dependence of j_c for both uniform and fast rising pulses suggest that the current, regardless of polarity, assists in the depinning of the DW. Only for the dc case does the data strongly reveal the influence of the electron pressure in promoting or hindering DW motion. © *2005 American Institute of Physics.* [DOI: 10.1063/1.1851434]

INTRODUCTION

There is currently a great interest in the effect of triggering domain-wall motion (DWM) through a spin-polarized current. This phenomenon was originally predicted by Berger[1] and has been unequivocally observed in multiple studies for the cases of domain walls (DW) forming in both continuous films[2] and submicron scale-patterned wires.[3–7] The effect is of crucial interest to the field of spintronics since it may provide an effective and efficient method for device switching. The process of magnetization reversal through DWM was, for a long time, considered inadequate in terms of speed. However, recent theories,[8,9] simulations,[10] and experiments,[5,7] point toward the possibility of fast reversal through current-induced domain-wall motion (CIDWM). Furthermore, these studies indicate that the presence of even weak magnetic fields can dramatically boost the speed of the DWM.

In the case of magnetoresistive random access memory (MRAM) technology, some advantages offered by the CIDWM approach are lower power consumption, crosstalk reduction during the writing process, and simplified device architecture, making this technology extremely attractive. Yet understanding and controlling this phenomenon in real structures are demanding tasks. First, the interaction between the conduction electrons and a DW in the presence of applied fields leads to a complex dynamical behavior due to various coexisting physical processes. Second the behavior will depend on the intricate DW micromagnetic structure deter-mined by the nanostructure geometry. Thus, quantitative correlations between the field and critical currents in CIDWM can shed light on these effects and may ultimately optimize the control and efficiency of the mechanism.

EXPERIMENT

Experiments were carried out on the $Ni_{81}Fe_{19}$ patterns, as shown in Figs. 1(i) and 1(ii). These were fabricated over thermally grown SiO_2 substrates through e-beam lithography followed by a standard lift-off process. The structures consist
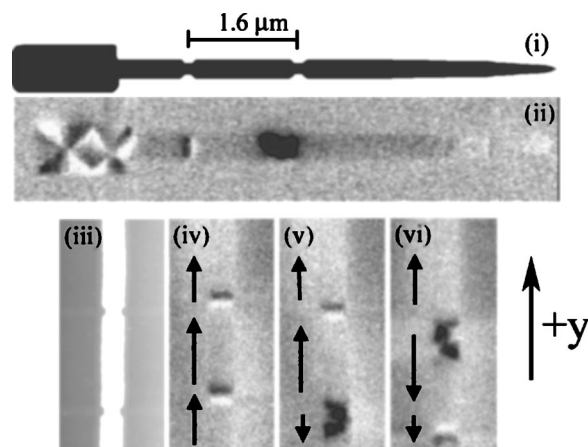

FIG. 1. (i) pattern geometry, (ii) MFM image of NiFe pattern, (iii) atomic force microscopy (AFM) image of sample section, (iv) MFM image at remanence after saturation, (v) initial condition for CIDWM experiments with a DW trapped in the lower constriction through $\mathbf{H}_{app}$, and (vi) MFM after applied current pulse with upward electron motion.
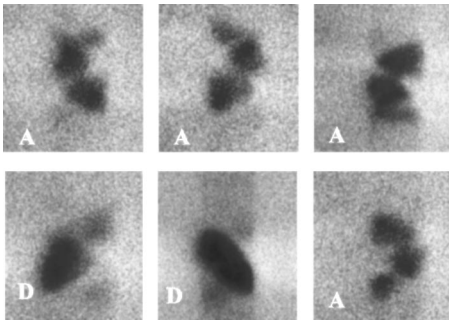
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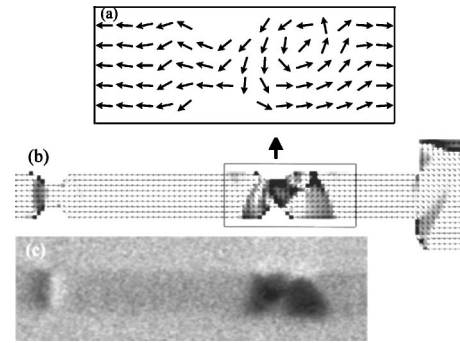
FIG. 2. Observed domain-wall configurations.

FIG. 3. Results from OOMMF micromagnetic simulation, (a) magnetization near constriction, (b) divergence of magnetization represented through pixel shade, and (c) MFM of section of sample.

of 300 nm wide, 40-nm-thick NiFe wires, containing two constrictions each roughly 220 nm wide. Following other similar studies,[3,5,6] elements are asymmetrical with a nucleation pad on one side and a sharp end on the other, ensuring DW nucleation from only one direction and the reproducibility of the process. Underlying Cr/Au electrodes were included to allow current injection through the magnetic element.

Experiments were performed by applying concurrent applied magnetic fields $\mathbf{H}_{app}$ and electrical currents to the sample and by using magnetic force microscopy (MFM) to evaluate the resulting effects. The samples were magnetically initialized by saturating the magnetization in the upward ($+y$ in Fig. 1) direction, and then sweeping $\mathbf{H}_{app}$ in the opposite direction until a DW nucleates from the lower pad edge and propagates towards the lower constriction. At this point, the section of the pattern below the lower constriction has reversed the direction of its magnetization. This switching event typically occurs near $\mathbf{H}_{app}=-165$ Oe. After removing the $\mathbf{H}_{app}$, MFM images, as shown in Fig. 1(v), confirm the capture of a tail-to-tail (or head-to-head) DW in the lower constriction. The magnetic configurations, with a DW trapped in constriction, were found to be stable and not affected by a low moment MFM tip. MFM images were taken, in order to determine if CIDWM had occurred, after applying uniform or pulsed electrical current through the sample, in presence of easy-axis bias magnetic fields of various magnitudes. In the case of applied current pulses, rise times were roughly below 20 ns and decay was exponential with fall times on the order of 1 μs. Uniform currents, on the other hand, were ramped very slowly with rise times near 400 μs and pulse durations of 400 ms. Repetition of this process at different field and current combinations, allowed us to generate the critical current versus applied field curves.

RESULTS AND DISCUSSION

Fig. 2 shows MFM images of the six types of DWs, which were observed to be trapped in a stable manner within the constrictions. It is readily apparent that each structure can be obtained from horizontal and vertical mirror reflections from two basic structures, labeled *A* and *D*. Type *D* shows an accumulation of magnetic charge at the constriction, forming a line diagonal to the axis of the element. Type *A* is more complex, but the magnetization distribution can be visualized in Fig. 3(a) by means of micromagnetic simulations. The result, using the public OOMMF simulation code with

standard parameters for NiFe $M_S=8.6\times10^5$ A/m, $A_{ex}=1.3\times10^{-11}$ J/m and with a cell size of 10 nm, suggests a vortex trapped near the constriction. Rendition of the divergence of the magnetization in pixel shading, shown in Fig. 3(b), indeed resembles the MFM image of the actual domain structure. The simulations also predict with remarkable accuracy the experimental switching field values.

We observed that by applying fast rising current pulses (of either polarity) above a certain excitation threshold (~5 $\times10^{11}$ A/m^2) yet below the motion threshold (~7.5 $\times10^{11}$ A/m^2), the pattern can be transformed from one state into any of the five other possible states. This suggests, as described by Berger,[1] that the current pulse may "jiggle" the DW thereby exciting the modes of DW oscillation, and the system subsequently relaxes into one of the six available states. For current pulses (fast rising) above ~7.5 $\times10^{11}$ A/m^2 and at $\mathbf{H}_{app}\sim0$, we observed CIDWM. An example of this effect is shown in Figs. 1(v) and 1(vi) where DW at the lower constriction has moved to upper constriction, thereby reversing the magnetization of the central segment. Reversible CIDWM was consistently observed for all observed DW types, although the DW type was not necessarily conserved after the displacement. We can toggle between the two trapped states, i.e., alternatively displacing the DW between the two sites by reversing the polarity of electrical current pulse and maintaining the amplitude above the critical threshold. However, since these high current densities cause significant electromigration and sample deterioration, only few repetitions of this event can only be observed with a given sample. In general, our observations are in agreement with previous studies,[3–7] and we can confirm that the DW can be displaced in the direction of electron motion in absence of an external-applied magnetic field (zero-field measurements include the Earth's magnetic field).

The effect was originally described by Berger,[1] as a transfer of spin angular momentum from the conduction electrons to the more localized magnetic moments that compose the DW. In this model, the spin-polarized current exerts a spin torque on the DW magnetization and may induce its motion. However, as the current transverses the DW, it is well recognized that there are other physical processes, such as the generation of an oersted field from the current that may also contribute to magnetization reversal. Furthermore, several other current-induced effects may reduce the local
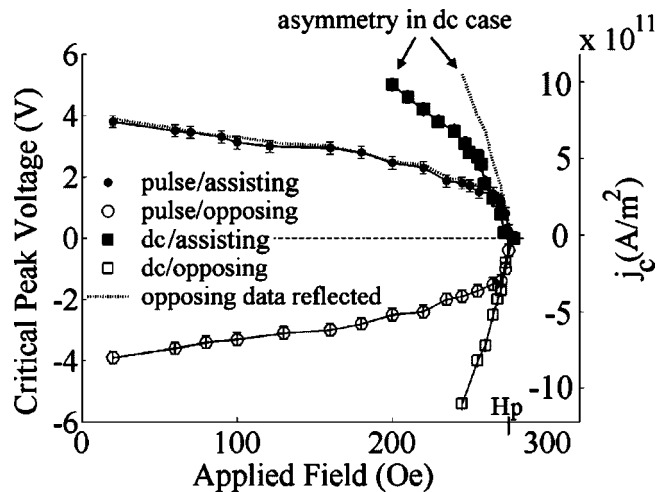
FIG. 4. Plot of critical current densities vs applied magnetic field. Pulse (circle) and dc (square) critical currents for the case of ($j_c > 0$) electron pressure *assisting* the magnetic field in triggering DWM (shaded symbol), and for the case of ($j_c < 0$) electron motion *opposing* the effect of the field (open symbol). The dotted lines correspond to the *opposing case* data reflected with respect to the $j_c=0$ axis (i.e., the absolute value of the critical currents). Only in the fast rising pulse case does the dotted line overlap the $j_c > 0$ data.

pinning forces on the DW, independent of the current direction. Some of these depinning mechanisms are joule heating, excitation of modes of DW oscillation,[1] and local DW deformation induced by the current.[11]

To shed some light on the effects of current on DW pinning, we studied the behavior of CIDWM in the presence of applied fields and the results are shown in Fig. 4. For each data point, the sample was initialized by trapping a dark, *A*-type DW of the same symmetry in the same constriction. The plot contains the data corresponding to DWM with both uniform and pulse current excitations. The critical current densities were calculated directly from critical voltages and ignoring joule heating of the sample. For $j_c > 0$, the direction of $\mathbf{H}_{app}$ as well as the electron pressure act in the same direction and both assisting DWM. Negative currents $j_c < 0$ correspond to the case where $\mathbf{H}_{app}$ and electron pressure act in opposite directions. For both types of current excitation, data confirm that the current assists in the depinning of the DW, regardless of direction of electron motion. In general, the order of magnitude of the critical current densities appears to be in agreement with other similar experiments,[4,5] yet about an order of magnitude lower than some theoretical precictions.[9] Results, however, show significant differences between the field dependence of j_c in the uniform and pulsed excitation cases. For the pulsed case, j_c appears to be more

nonlinear with $\mathbf{H}_{app}$, in comparison to the dc case. In this data, the critical values slightly below H_p are higher for the dc case, however, additional data (not shown) suggest that the magnitude of this current depends on pulse duration. For all measured samples, however, critical currents for the dc case increase much faster with reducing field than those measured for the fast rising pulse case. In fact, for fields below ~200 Oe it was not possible to depin and displace the DW with dc current (required currents were high enough to burn the sample).

More interestingly, within experimental accuracy, the data for the fast rising pulse case are nearly symmetric about horizontal axis. This is surprising, especially at high fields/low currents where joule heating is low, since one would expect that the opposing direction of the pulsed current should hinder the DWM. This suggests that the depinning mechanisms, independent of current direction, mentioned before are dominant. The dc data, in contrast, show a much stronger antisymmetric behavior with respect to current direction at this high-field range below H_p. That is, the slope of the j_c vs $\mathbf{H}_{app}$ line is much steeper in the lower quadrant, suggesting that the electron pressure either assists or impedes the action of the $\mathbf{H}_{app}$ in reversing the central domain. Thus, it appears that the DWM triggering mechanisms dominating with these two types of current dynamics are inherently different. By additionally plotting the absolute values of the critical currents for the data corresponding to electron motion opposing the direction of DWM, the asymmetry in the dc case is clearly revealed.

ACKNOWLEDGMENTS

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