360° domain walls: stability, magnetic field and electric current effects

Jinshuo Zhang1, Saima A Siddiqui2, Pin Ho2, Jean Anne Currivan-Incorvia2,3, Larysa Tryputen4, Enno Lage4, David C Bono1, Marc A Baldo1, and Caroline A Ross1,4

1 Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2 Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
3 Department of Physics, Harvard University, Cambridge, MA 02138, USA
4 Author to whom any correspondence should be addressed.

E-mail: carross@mit.edu

Keywords: spintronics, magnetic domain wall, anisotropic magnetoresistance, micromagnetic simulation

Supplementary material for this article is available online

Abstract

The formation of 360° magnetic domain walls (360DWs) in Co and Ni80Fe20 thin film wires was demonstrated experimentally for different wire widths, by successively injecting two 180° domain walls (180DWs) into the wire. For narrow wires (<50 nm wide for Co), edge roughness prevented the combination of the 180DWs into a 360DW, and for wide wires (200 nm for Co) the 360DW was unstable and annihilated spontaneously, but over an intermediate range of wire widths, reproducible 360DW formation occurred. The annihilation and dissociation of 360DWs was demonstrated by applying a magnetic field parallel to the wire, showing that annihilation fields were several times higher than dissociation fields in agreement with micromagnetic modeling. The annihilation of a 360DW by current pulsing was demonstrated.

Magnetic domain walls (DWs) in narrow wires provide a data token for devices such as racetrack memory and logic gates [1–3]. DW devices maintain the traditional merits of magnetic data storage including non-volatility and high density, but offer new functionality including fully electrical operation by using spin torque transfer to manipulate the DWs and magnetoresistance to detect them. This can in principle enable faster switching speeds and lower energy consumption compared to DRAMs and other semiconductor devices [4]. Many proposed DW devices are made from nanowires containing 180DWs, where the orientation of magnetization rotates through 180° in narrow wires compared to that of a 180DW. 360DWs are not known as 1D skyrmions [9], an example of a class of topologically protected structures which are under intense study due to their stability and device applications [10].

360DWs have been observed both in continuous ferromagnetic films [11] and in ferromagnetic nanostructures such as thin film rings or ellipses [12–14]. The orientation of magnetization rotates through 360°, and due to the opposite sense of core magnetization in the two component 180DWs, magnetic flux closure reduces the stray field around the 360DW in a thin film wire compared to that of a 180DW [15]. 360DWs are not expected to be translated by an applied field, but instead can be dissociated or annihilated. However, micromagnetic simulations predict that a current can translate the 360DW via spin torque transfer [15]. Moreover, instead of Walker Breakdown as observed in 180DWs, a 360DW is predicted to undergo annihilation at a sufficiently high spin current density. Simulations predict that 360DWs of different chirality can be filtered.
and 360DWs have been proposed for use in magnetic sensors and as an alternative to 180DWs in memory and logic. 360DWs in magnetic wires have been detected using magnetic force microscopy (MFM), scanning electron microscopy (SEM) with polarization analysis, and anisotropic magnetoresistance (AMR) measurements, in which the formation of a 360DW results in a decrease of resistance. There has been considerable theoretical and modeling work on the behavior of 360DWs, but there have been no systematic experimental reports on the formation of 360DWs, their response to a field as a function of wire width, nor any observation of current-driven motion of a 360DW. In this article, we first demonstrate the formation and stability of 360DWs in specifically designed Co and Ni$_{80}$Fe$_{20}$ nanostructures of different widths with in-plane magnetization. We then demonstrate the effect of applied magnetic fields or injected current pulses on 360DWs using AMR measurements for Ni$_{80}$Fe$_{20}$ samples and MFM measurements for Co samples. Ni$_{80}$Fe$_{20}$ has a relatively large AMR response so that individual DWs can be detected in situ, but its low switching field renders DWs vulnerable to perturbation by the stray field of an MFM tip. On the contrary, Co has a lower AMR but its higher switching field facilitates direct imaging of the stray field of DWs by MFM. Therefore studies of 360DWs in both NiFe and Co provide complementary information. We relate the experimental results to micromagnetic simulations.

The method used to generate a 360DW is similar to previous work. The structures consist of a magnetic thin film wire in the shape of an arc, with width varying from 50 to 200 nm, connected to a round injection pad of 1 μm diameter. The structures were made from a thin film stack of Ta (5 nm)/Ni$_{80}$Fe$_{20}$ (10 nm)/Au (5 nm) or Ta (5 nm)/Co (10 nm)/Au (5 nm) which was deposited by magnetron sputtering (5 cm diameter target, 100 W, 200 W).

Figure 1. (a) Simulation of a transverse 180DW and a 360DW inside a Co arc, 10 nm thick and 120 nm wide. Arrows show magnetization, red (positive) and blue (negative) indicate the component of magnetization along the wire length, the x-direction. Insets are the simulated z-component of the stray field at a height of 3 nm above the surface of the sample. Blue and red represent up and down directions. (b) The upper AFM image shows a 120 nm wide Co wire and pad used to generate a 360DW, and the lower MFM image illustrates a 360DW in the wire. (c) MFM images of other Co samples with wire width of 50, 80, 150 and 200 nm.
and growth rates of 0.15–0.30 nm s\(^{-1}\) for different materials) on a Si substrate with native oxide, at an Ar pressure of 1 mTorr and a base pressure better than 5 \(\times\) 10\(^{-8}\) Torr. A bilayer resist\(^{[25]}\) consisting of 4% polymethyl-methacrylate (PMMA) of thickness 30 nm and 2% hydrogen silsesquioxane (HSQ) of thickness 40 nm was spin coated on the magnetic film then exposed using an Elionix E-125 e-beam lithography tool with a dose of 38 mC cm\(^{-2}\). The HSQ layer was developed using 4% NaCl + 1% NaOH in water solution for 20 s, washed with DI water and carefully dried by a nitrogen blow gun. The underlying PMMA layer was then removed with O\(_2\) plasma at a pressure of 6 \(\times\) 10\(^{-3}\) Torr at 90 W power for 2 min. Using these patterned bilayer resists as an etch mask, the metal film was then etched using an Ar ion beam with a beam current of 10 mA and pressure of 2 \(\times\) 10\(^{-4}\) Torr. The etching was monitored using an end-point detector. Since the PMMA acts as a sacrificial layer, the resist stack could then be removed with hot 1165 solvent [MicroChem Corp.] and sonication after the ion beam etching. An AFM image of a typical structure is shown in the upper panel of figure 1(b). For AMR characterization, we used low moment magnetic tips [Bruker MESP-LM] in order to reduce the interaction between the sample and the stray field of the tip. Lift height was set to 50 nm during the second MFM pass to ensure relatively small interaction between sample and tip as well as to obtain clear phase information. The scale for the MFM phase images shown in this paper is \(\pm 3\). 

Micromagnetic simulations were performed using the OOMMF package\(^{[26]}\). For Co the exchange constant \(A = 10^{-5}\) erg cm\(^{-1}\), saturation magnetization \(M_s = 1000\) emu cm\(^{-3}\), \(\alpha = 0.02\), \(\beta = 0.03\) and anisotropy \(K_u = 10^6\) erg cm\(^{-3}\) with a random orientation for each cell to simulate a polycrystalline film. For NiFe the exchange constant was \(A = 1.3 \times 10^{-4}\) erg cm\(^{-1}\), saturation magnetization \(M_s = 800\) emu cm\(^{-3}\), anisotropy \(K_u = 0\), \(\alpha = 0.02\) and \(\beta = 0.03\). The length and thickness of the simulated wires were 10 \(\mu\)m and 10 nm, respectively. The cell size was (5 nm)\(^3\) in most simulations, though (2 nm)\(^3\) cells were used for comparison: this predicted a critical field and a critical current for annihilation that were higher by about 15%, but the results were qualitatively the same.

We describe first the formation and stability of 360DWs in Co arcs. In order to generate a 360DW, an in-plane field sequence was applied perpendicular to the arc. \(H_y = +3000\) Oe was applied to fully saturate the magnetization and form the first 180DW with its core magnetized along \(+y\) at the center of the arc at remanence. \(H_y = −300\) Oe was then applied, a field sufficient to reverse the magnetization in the round pad but not high enough to reverse the magnetization in the arc due to its higher shape anisotropy. A second 180DW with opposite sense to the first 180DW was formed at the interface between the round pad and the arc. The two 180DWs combine to form a 360DW aided by their magnetostatic attraction\(^{[14]}\). AFM and MFM images of a Co sample of width 120 nm are shown in figure 1(b). The dark and bright contrast observed at the center of the arc qualitatively resembles the calculated stray field around the 360DW in figure 1(a) and confirmed the presence of a 360DW.

Co samples with different arc widths of 50, 80, 120, 150 and 200 nm were tested to study the 360DW stability as a function of arc width. We expect TWs to be energetically preferable within the width range according to micromagnetic simulations in Co nanowires. The 80, 120 and 150 nm samples successfully formed a 360DW in the arc. In the sample with 50 nm wire width, two 180DWs of opposite sense were formed but remained separate in the arc without combining into a 360DW (the bright contrast originates from the second 180DW). This is attributed to pinning: the amplitude of line edge roughness is expected to be independent of wire width\(^{[25]}\), but the resulting changes in wire width are proportionately larger for narrower wires. The length of a 180DW also decreases with decreasing wire width\(^{[2]}\), making it more sensitive to high frequency edge roughness. These factors lead to stronger pinning of the 180DWs in narrower wires, which impedes their combination into a 360DW.

The sample with wire width of 200 nm, no 360DW was observed. MFM images of the sample after applying the initial saturation field of \(H_y = +3000\) Oe showed a 180DW with transverse configuration as illustrated by dark contrast at the arc center. This result shows that a 180DW could be formed but the second 180DW is assumed to annihilate the first one instead of forming a 360DW. The reduced influence of edge roughness may have enabled the second 180DW to approach the first at a higher velocity, which promotes annihilation.

The experimental results for 360DW formation under transverse field cycling agree with the prediction of micromagnetic modeling, figure 2(a), for Co arcs. Simulations were performed with the same field sequence of \(H_y = +3000\) Oe followed by \(H_y = −200\) Oe, for wire widths of 50, 100, 200 and 300 nm. The arc shape in the model leads to edge roughness due to the finite cell size. The 50 nm wide model wire was unable to form a 360DW because the second 180DW did not propagate far enough to combine with the first 180DW. The 100 and 200 nm arcs did produce 360DWs, but in the 300 nm wide model wire the 360DW spontaneously annihilated.

The effect of magnetic field on 360DWs was studied experimentally in both Ni\(_{80}\)Fe\(_{20}\) and Co samples and characterized by AMR and MFM, respectively. A SEM image of a Ni\(_{80}\)Fe\(_{20}\) sample is shown in figure 3(a), which...
was 200 nm wide and 10 nm thick. Vortex DWs are energetically favorable in this material and geometry compared to TWs, according to micromagnetic simulations. A small DC current was applied between the outer two electrodes and the voltage between the inner two electrodes was measured in order to obtain the resistance. This reference DC current was lower than 5 \( \mu \text{A} \), corresponding to an average current density of less than 2 \( \times 10^9 \) A m\(^{-2} \) in the arc, which was 0.001–0.01 times the current density reported to move a DW in Ni\(_{80}\)Fe\(_{20}\) nanowires \([8, 27–30]\). Therefore the effect of the measurement current on the wall was neglected.

As shown in the round dot line in figure 3(b), a head-to-head 180DW was formed by applying \( H \)= +3000 Oe, then a field in the \(+x\) direction was applied, starting from zero and increasing with a step size of 1 Oe. The resistance was measured after each field step. A change of \( \Delta R = 0.055 \pm 0.005 \) \( \Omega \) was observed at 5 Oe based on ten repeated measurements, indicating movement of the 180DW to the right, out of the area between the inner two electrodes. The increase of the resistance is due to the AMR effect from the 180DW: the resistance is lower at the DW because the magnetization is locally perpendicular to the electron flow. The AMR follows the relation

\[
\frac{\Delta \rho (H)}{\rho_{av}} = \frac{\Delta \rho}{\rho_{av}} \left( \cos^2 \theta - \frac{1}{3} \right)
\]

in which \( \Delta \rho (H) \) is the change of resistivity and \( \theta \) is the angle between magnetization and electron flow \([31]\). If a field was applied in the \(-x\) direction, a similar resistance jump of \( \Delta R = 0.053 \pm 0.005 \) \( \Omega \) was observed at \(-6\) Oe based on ten repeated measurements, shown in the square dot line in figure 3(b). This indicated the 180DW moving to the left, out of the area between the inner two electrodes. Out of 20 total measurements, the resistance jump was very similar for eight and nine of the measurements for fields along \(+x\) and \(-x\), respectively.
The other three tests gave either no resistance change or a change of \( \Delta R = 0.03 \) \( \Omega \) which may have indicated differences in the DW structure or location. Other groups have also shown DW AMR in large numbers of repeated tests [18]. We used the eight and nine measurements to calculate \( \Delta R \).

A field sequence of \( H_y = +3000 \) Oe followed by \( H_y = -300 \) Oe was then used to form a 360DW in the 200 nm wide Ni\(_{80}\)Fe\(_{20}\) wire, followed by a field in the \( +x \) or \( -x \) direction as shown in figures 3(c) and (d), respectively. In figure 3(c), a resistance jump of \( \Delta R = 0.078 \pm 0.007 \) \( \Omega \) based on ten measurements was observed at \( H_x \equiv +14 \) Oe. The higher resistance change confirmed the presence of a 360DW instead of 180DW and the higher value of \( H_x \) represents the critical field to dissociate a 360DW, overcoming the magnetostatic attraction between the two component 180DWs and separating them to form a reverse domain.

In comparison, in figure 3(d), a resistance jump of \( \Delta R = 0.075 \pm 0.007 \) \( \Omega \) was observed at \( H_x \equiv -84 \) Oe, much higher than the critical field in figure 3(c). This represents the critical field to annihilate the 360DW, in which the field compresses the 360DW, eventually eliminating it. The ratio of AMR change expected between a 180DW and a 360DW was calculated by exporting the magnetization distribution from OOMMF into MATLAB and determining the resistance based on equation (1). The AMR ratio was \( \frac{\Delta R_{360}}{\Delta R_{180}} = 1.46 \) for a Ni\(_{80}\)Fe\(_{20}\) nanowire with \( w = 200 \) nm and \( t = 10 \) nm, similar to the experimental result of \( \frac{\Delta R_{360}}{\Delta R_{180}} = 1.39 \pm 0.09 \).

Simulations in Ni\(_{80}\)Fe\(_{20}\) nanowires were carried out to calculate the critical fields for annihilation and dissociation of a 360DW versus wire width, figure 2(b). We first initiated a 360DW at the center of the wire, allowed it to relax, then applied a field in either the \( +x \) or \( -x \) direction along the wire to dissociate or annihilate the 360DW, respectively. We increased the field from 0 with a step size of 10 Oe in order to find the critical value. As shown in figure 2(b), the critical fields for annihilation and dissociation decreased by about 40% and 80%, respectively with an increase of wire width from 50 to 300 nm. The 360DW became less symmetrical as the width
increased, with the two component 180DWs tilting towards each other at one side of the wire, making the 360DW less stable. It has also been shown in [18] that the 360DW forms a much less stable vortex structure with increasing wire width.

For a model Ni80Fe20 nanowire of width $w = 200$ nm and thickness $t = 10$ nm, the critical field to dissociate a 360DW is $H_x = +75$ Oe and to annihilate it is $H_x = -310$ Oe. The modeling predicted much higher absolute values of the annihilation and dissociation fields than were measured experimentally, which may be a result of the zero temperature of the model and the lack of extrinsic defects that could initiate annihilation and dissociation. However, both model and experiment agree in showing annihilation field several times larger in magnitude than dissociation fields.

The effect of a magnetic field on 360DWs in Co nanowires were examined using MFM. As shown in figure 4(a), a 360DW was first formed in a Co sample with wire width of 80 nm by applying $H_x = +3000$ Oe then $H_x = -300$ Oe. Different magnetic fields were applied in the $+x$ direction to dissociate the 360DW. The 360DW was unchanged for $H_x = +125$ Oe, but after the application of $H_x = +150$ Oe, the two component 180DWs moved apart forming a reverse domain. After the application of $H_x = +200$ Oe, the component 180DWs moved further such that the left-hand bright-contrast wall moved into the injection pad and the right dark-contrast wall moved to the end of the wire. The reversal of the wire is evident from the change in contrast from bright to dark at the tip of the wire, labeled by the black circles in figure 4. A similar dissociation process was observed in a Co sample with 150 nm wire width, figure 4(b), except that the field steps did not capture the presence of two separate 180DWs in the wire. In the 150 nm wide wire, dissociation occurred at a field between 125 and 150 Oe.

360DW annihilation in a Co sample was demonstrated by applying a field in the $-x$ direction. The same field sequence as in figure 4 was applied initially to form a 360DW at the center of the arc. The MFM measurements are shown in the supplement (figure S1). The 360DW remained stable in the arc for $-H_x = -310$ Oe. The 360DW disappeared after applying a field of $H_x = -700$ Oe, but different from the dissociation results in figure 4, the right-hand end of the wire retained its bright contrast before and after the annihilation. This proves that the magnetization direction remained the same in the arc, indicating annihilation instead of dissociation of the 360DW. The field for annihilation ($-700$ Oe) was also much larger than that for dissociation ($+150$ Oe) in the 150 nm wide Co wire, confirming the same trend as seen in the Ni80Fe20 samples and in micromagnetic simulations.

The effects of current on 360DWs were examined in 150 nm wide Co samples. Two electrodes were placed on top of the sample as shown in figure 5(a), labeled $1^+$ and $1^-$, and the conventional current flowed from the right electrode to the left electrode. Figure 5(b) is an MFM image of the sample initiated with a 360DW at the arc center. Current pulses of $+2$ V, $+4$ V or $+6$ V amplitude and 200 ns duration were then injected into the sample, corresponding to current densities of approximately $1.2$, $2.4$ or $3.6 \times 10^{12}$ A m$^{-2}$ respectively in the arc, averaged over the Ta/Co/Au stack. A delay of 3 s was inserted between each pulse to minimize Joule heating. From MFM imaging there was no observed effect of current pulses with amplitude of 2 V. Figure 5(c) shows the 360DW after two pulses of 4 V, which moved $\sim 200$ nm to the right, indicating a small current-driven 360DW motion. We did not see any further translation after two additional pulses of 4 V, but after ten additional pulses the 360DW was no longer visible.

**Figure 4.** (a) A series of MFM images of a 360DW in a Co wire with width of 80 nm after application of different fields in the $+x$ direction, showing separation into two 180DWs at $+150$ Oe and movement of the walls out of the wire at $+200$ Oe; (b) A series of MFM images of a 360DW in a Co wire with width of 150 nm after application of different fields in the $+x$ direction. The wall was dissociated and the two 180DWs moved out of the wire between 125 and 150 Oe. In both samples dissociation is evident from the change of contrast at the tip of the wire from light in the first panel to dark (black circle).
pulses of 4 V the 360DW disappeared as shown in figure 5(d). Since the current is limited to the region of the arc between the two electrodes, the current-driven 360DW will not be able to move further than the electrode. Moreover, from our tests the phase contrast of a 360DW can still be observed at 150 nm lift height, which means that even if the 360DW is beneath the arc, we should still be able to see the phase contrast. As shown in figure 5(d), MFM did not reveal the 360DW remaining under the Au contact, implying that the 360DW was annihilated.

An estimation of the temperature increase from Joule heating at the end of a current pulse was made based on the calculation in [33]:

\[
\tau(t) = \frac{wh^2}{\pi \mu \sigma_w \rho C_s} \ln \left( \frac{4 \sqrt{\mu_i I}}{w_G} \right)
\]

where width \( w = 300 \) nm, thickness \( h = 20 \) nm (including the seeding layer and capping layer), current density \( J = 3.3 \times 10^{12} \) A m\(^{-2}\), thermal conductivity \( \mu_1 (\text{Si}) = 8.8 \times 10^{-3} \) m\(^2\) s\(^{-1}\), electrical conductivity \( \sigma_1 (\text{Co}) = 10^7 \) (\( \Omega \text{m} \))\(^{-1}\), material density \( \rho = 8900 \) kg m\(^{-3}\), heat capacity \( C_s = 400 \) J (kg K\(^{-1}\)), pulse duration \( t = 200 \) ns and \( w_G = w/2 = 150 \) nm. By substituting the parameters for the 4 V pulse, an approximate maximum temperature increase of 36 K was obtained.

Previous simulation results [15] predicted that in a smooth-edged nanowire with zero anisotropy, a spin current will translate a 360DW, and at high enough spin current density will annihilate it. However, our experiments showed annihilation after only a small translation. The limited current-driven motion of the 360DW is attributed to the anisotropy from Co and extrinsic pinning from edge roughness. This was confirmed by measurements of current-driven motion of 180DWs in the same sample. Ten identical 200 ns current pulses were injected at voltages of +2 to +6 V (the highest voltage led to damage to the sample), but the 180DW was not translated. This suggests that DWs are pinned in the Co nanowires [34], and the current therefore annihilated the 360DW without moving it.

To assess the role of edge roughness, simulations (at zero temperature) were performed for Co nanowires with the same random anisotropy as described above as well as with an edge roughness amplitude \( \Delta = 3\% \) of the average wire width, produced by removing cells from the side of the wire randomly. Both 360DWs and 180DWs were only able to move by \( < 100 \) nm when a current density of \( 5.3 \times 10^{12} \) A m\(^{-2}\) was applied. On increasing the current density to \( 7.1 \times 10^{12} \) A m\(^{-2}\), the 180DW translated further while the 360DW was annihilated after an initial \( \approx 100 \) nm motion. This shows the importance of the edge properties on the motion of the DWs.

The experimental results show that current pulses provided an effective method for annihilating the 360DW. It required \( -700 \) Oe to annihilate a 360DW in the 80 nm wide Co sample but only \( +150 \) Oe to move a 180DW. For the current pulsing, annihilation of the 360DW occurred at 4 V pulse amplitude but moving a 180DW required at least 6 V. The joule heating during current pulsing may contribute to destabilizing the wall, but the temperature decreased too quickly to enable an accurate measurement [32]. We estimated above that the

---

Figure 5. (a) AFM of Co sample with wire width 150 nm with gold electrodes on top, with \( I^- \) and \( I^+ \) indicating the direction of current flow. (b) MFM of the sample after initializing a 360DW. (c) MFM of the sample after injecting two current pulses with +4 V amplitude and 200 ns duration showing a small translation of the 360DW. (d) MFM of the sample after injecting ten more current pulses with +4 V amplitude and 200 ns duration, showing annihilation of the 360DW.
temperature increase would be \( \sim 36 \) K based on the results in [33, 35], which is also consistent with a measurement based on resistance change [36].

The modeling illustrates the different 360DW annihilation mechanism between using current pulses and using external field, making current pulses particularly effective in 360DW annihilation. Figures 6(a) and 6(b) show snapshots of the simulated 360DW annihilation processes driven by field and current in a 100 nm wide and 10 nm thick wire, using the same parameters as in figure 2. A cell size of \((2 \text{ nm})^2\) was used in this set of simulations. In figure 6 the 360DW develops a trapezoidal shape with the narrower side at the bottom of the figure. In the field-driven annihilation process, the field pushes the two component 180DWs together and when they are close enough the 360DW is annihilated starting from its narrower edge. On the contrary, in the current-driven annihilation process, the current translates the 360DW, which moves with an oscillatory motion and becomes unstable, eventually closing up from the narrower edge. During the annihilation process, the exchange energy provides a barrier for annihilation. At the critical annihilation field of 320 Oe, the maximum exchange energy was \(1.24 \times 10^{-17} \text{ J}\), while at the critical annihilation spin current velocity of \(u = 180 \text{ m s}^{-1}\) (corresponding to a current density of \(J = 6.3 \times 10^{12} \text{ A m}^{-2}\)), the maximum exchange energy was only \(0.78 \times 10^{-17} \text{ J}\). The difference points to the instability of the 360DW under current as a contributing factor to the annihilation process.

In summary, 360DWs were formed in both Ni_{80}Fe_{20} and Co wires with a range of widths. 360DW dissociation and annihilation were experimentally observed by AMR measurements in Ni_{80}Fe_{20} and by MFM measurements in Co nanowires, and the critical fields were determined. The experimental results were compared with micromagnetic simulations, both of which showed that field-driven annihilation requires several times larger field than field-driven dissociation, though the magnitude of the critical fields was higher in the simulations. The effects of current on 360DWs in Co were examined using MFM. Current produced a small translation of the 360DW then led to its annihilation at \(2.2 \times 10^{12} \text{ A m}^{-2}\), a current smaller than that required to translate a 180DW in a Co nanowire of the same width. The high fields required for translation are attributed to edge pinning in the Co, but the relatively low current required for annihilation is consistent with the lower energy barrier for current-driven annihilation compared to field-driven annihilation predicted by micromagnetic modeling. The modeling also predicts a different annihilation mechanism for current and field. These results provide experimental evidence for the formation and manipulation of 360DWs, which are important in the study of memory and logic devices based on both 180DWs and 360DWs.

Acknowledgments

This work was supported by the NSF under award ECCS 1101798. Shared facilities of the MIT NanoStructures Laboratory and Center for Materials Science and Engineering (NSF DMR1419807) were used.
References

[1] Parkin S S P, Hayashi M and Thomas I 2008 Magnetic domain-wall racetrack memory Science 320 190–4
[2] Curriuvan J A, Jang Y, Mascaro M D, Baldo M A and Ross C A 2012 Low energy magnetic domain wall Logic in short, narrow, ferromagnetic wires IEEE Magn. Lett. 3 500104
[3] Allwood D A, Xiong G, Faulkner C, Atkinson D, Petit D and Cowburn R 2005 Magnetic domain–wall logic Science 309 1688–92
[4] Vogelsang T 2010 Understanding the energy consumption of dynamic random access memories Proc. 2010 43rd Annual IEEE/ACM Int. Symp. on Microarchitecture pp 363–74
[5] Thiaville A, Nakatani Y, Milatt J and Suzuki Y 2007 Micromagnetic understanding of current-driven domain wall motion in patterned nanowires Europhys. Lett. 69 990
[6] McMichael R D and Donahue M J 1997 Head to head domain wall structures in thin magnetic strips IEEE Trans. Magn. 33 4167–9
[7] Beach G S D, Nistor C, Knutson C, Tsio M and Erskeine J L 2005 Dynamics of field-driven domain–wall propagation in ferromagnetic nanowires Nat. Mater. 4 741–4
[8] Yamaguchi A, Ono T, Nasu S, Miyake K, Mibu K and Shinjo T 2004 Real-space observation of current–driven domain wall motion in submicron magnetic wires Phys. Rev. Lett. 92 77205
[9] von Bergmann K, Kubetzka A, Pietsch O and Wiesendanger R 2014 Interface–induced chiral domain walls, spin spirals and skyrmions revealed by spin-polarized scanning tunneling microscopy J. Phys.: Condens. Matter 26 394002
[10] Yu X et al 2012 Skyrmion flow near room temperature in an ultralow current density Nat. Commun. 3 988
[11] Cho H S, Hou C, Sun M and Fujihara H 1999 Characteristics of 360°–domain walls observed by magnetic force microscope in exchange-biased NiFe films J. Appl. Phys. 85 5160–2
[12] Henn M et al 2008 360° domain wall generation in the soft layer of magnetic tunnel junctions Appl. Phys. Lett. 92 072501
[13] Porter X and Pefiod–Long A 2000 The formation of 360° domain walls in magnetic tunnel junction elements Appl. Phys. Lett. 76 754–6
[14] Jang Y, Bowden S R, Mascaro M, Unguris J and Ross C 2012 Formation and structure of 360° and 540 degree domain walls in thin magnetic strips Appl. Phys. Lett. 100 062407
[15] Mascaro M D and Ross C A 2010 ac and dc current-induced motion of a 360° domain wall Phys. Rev. B 82 214411
[16] Zhang J and Ross C A 2013 Gold shunt pads as a chirality filter for current–driven 360° domain wall motion in a ferromagnetic wire Appl. Phys. Lett. 103 162411
[17] Diegel M, Matthies R and Halder E 2004 360° domain wall motion for sensor applications IEEE Trans. Magn. 40 2655–7
[18] Thomas L, Hayashi M, Moriya R, Retten C and Parkin S 2012 Topological repulsion between domain walls in magnetic nanowires leading to the formation of bound states Nat. Commun. 3 810
[19] Nam C and Ross C A 2013 360° degree domain walls monitored by anisotropic magnetoresistance measurements J. Appl. Phys. 113 123910
[20] Nam C, Mascaro M and Ross C A 2010 Magnetostrictive control of vortex chirality in Co thin film rings Appl. Phys. Lett. 97 012505
[21] Mascaro M D, Kormer H S, Nam C, Ng B G and Ross C A 2011 360° domain wall mediated reversal in rhombic Co/Cu/NiFe magnetic rings Appl. Phys. Lett. 98 252506
[22] Muratov C and Osipov V 2008 Theory of 360° domain walls in thin ferromagnetic films J. Appl. Phys. 104 053908
[23] Roy P, Eyeriniotis T and Barnes C H W 2010 Micromagnetic simulations of spin–wave normal modes and the resonant field–driven magnetization dynamics of a 360° domain wall in a soft magnetic stripe Phys. Rev. B 82 134411
[24] Kunz A 2009 Field induced domain wall collisions in thin magnetic nanowires Appl. Phys. Lett. 94 132502
[25] Curriuvan J A et al 2014 Polymethyl methacrylate, hydrogen silsesquioxane bilayer resist electron beam lithography process for etching 25 nm wide magnetic wires J. Vac. Sci. Technol. B 32 021601
[26] Donahue M J and Porter D G 1999 OOMMF User’s Guide Interagency Report NISTIR 6376 (Gaithersburg, MD: National Institute of Standards and Technology)
[27] Malinowski G, Boule O and Kläui M 2011 Current-induced domain wall motion in nanoscale ferromagnetic elements J. Phys. D: Appl. Phys. 44 384005
[28] Kläui M et al 2005 Controlled and reproducible domain wall displacement by current pulses injected into ferromagnetic ring structures Phys. Rev. Lett. 94 106601
[29] Vernier N, Allwood D A, Atkinson D, Cooke M D and Cowburn R P 2004 Domain wall propagation in magnetic nanowires by spin–polarized current injection Europhys. Lett. 65 526
[30] Hu X et al 2013 Discontinuous properties of current–induced magnetic domain wall depinning Sci. Rep. 3 3080
[31] O’handley R C 2000 Modern Magnetic Materials: Principles and Applications vol 830622677 (New York: Wiley)
[32] Yamaguchi A et al 2005 Effect of Joule heating in current–driven domain wall motion Appl. Phys. Lett. 86 012511
[33] You C Y, Sung J M and Joe B K 2006 Analytic expression for the temperature of the current–heated nanowire for the current–induced domain wall motion Appl. Phys. Lett. 89 222513
[34] Hayashi M et al 2006 Influence of current on field–driven domain wall motion in permalloy nanowires from time resolved measurements of anisotropic magnetoresistance Phys. Rev. Lett. 96 197207
[35] Laufenberg M et al 2006 Temperature dependence of the spin torque effect in current–induced domain wall motion Phys. Rev. Lett. 96 046602
[36] Ho P, Zhang J, Curriuvan-Incorvia J A, Bono D C and Ross C A 2015 Field and current driven magnetic domain wall motion in disordered A1–FePt nanowires IEEE Magn. Lett. 6 1–4