Pinning Induced by Inter-Domain Wall Interactions in Planar Magnetic Nanowires

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We have investigated pinning potentials created by inter-domain wall magnetostatic interactions in planar magnetic nanowires. We show that these potentials can take the form of an energy barrier or an energy well depending on the walls' relative monopole moments, and that the applied magnetic fields required to overcome these potentials are significant. Both transverse and vortex wall pairs are investigated and it is found that transverse walls interact more strongly due to dipolar coupling between their magnetization structures. Simple analytical models which allow the effects of inter-domain wall interactions to be estimated are also presented.

There is great interest in developing memory [1] and logic [2] devices based upon the controlled motion and interaction of domain walls (DWs) in ferromagnetic planar nanowires. Such domain walls have particle-like properties which allow them to be propagated around complex circuits using rotating magnetic fields [3,4] or short electric current pulses [5], and hence they may be used to represent binary data in a similar way to electric charge in conventional microelectronics.

DWs in planar magnetic nanowires have head-to-head (H2H) or tail-to-tail (T2T) character (Fig 1(a)), and consequently they carry a net monopole moment (i.e. a localised excess of north (H2H) or south (T2T) magnetic poles). Therefore, to a first approximation DWs in adjacent nanowires will interact via a Coulomb-like potential: if the DWs have like monopole moments there will be a repulsive interaction, whereas if they have opposite monopole moments their interaction will be attractive. Understanding these effects and how they affect DW propagation is likely to be important to the development of DW based devices, where large nanowire densities will be desirable. So far there have been relatively few investigations into these effects, with studies characterizing attractive coupling between walls with opposite monopole moments for a limited range of nanowire geometries and DW structures [6,7]. We have also previously demonstrated that DW interaction energies are dependent to some degree on the DWs magnetization structure and chirality [8].

In this paper we use micromagnetic simulations and high resolution X-ray transmission microscopy to investigate pinning effects induced by inter-DW interactions in planar $Ni_{80}Fe_{20}$ nanowires. By measuring the applied fields required to overcome these interactions we show that DWs perceive the magnetostatic field of DWs in neighbouring nanowires as either energy wells or as energy barriers depending on the relative signs of their monopole moments, and that these barriers/wells are significant enough to "capture" and prevent the further motion of DWs propagating under the influence of applied field. Interactions between of both transverse and vortex DWs are investigated. We also present a simple analytical model which allows the effect of inter-wall interactions on DW propagation to be estimated.

Pairs of 33 nm thick, 440 nm wide $Ni_{80}Fe_{20}$ planar nanowires were fabricated on silicon nitride membranes by e-beam lithography with lift-off processing. Metallisation was achieved by thermal evaporation.

Magnetic X-ray transmission microscopy (M-TXM) with resolution better than 25 nm was performed at beamline 6.1.2 at the Advanced Light Source synchrotron [9,10]. In-plane magnetic contrast was achieved by differential imaging with left and right circularly polarized X-rays with the sample tilted at 30° to normal incidence. Magnetic fields could be applied in the sample plane in directions both parallel (H_x) and perpendicular (H_y) to the direction of magnetic contrast.

2D Micromagnetic simulations were performed using the OOMMF software package [11]. The cell size was 5 x 5 nm. Standard parameter were used to represent the material properties of $Ni_{80}Fe_{20}$ (Saturation magnetisation: M_S = 860 kA/m, exchange stiffness: A = 13 pJ/m, magnetocrystalline anisotropy constant: $K_1 = 0$).

Initially, we performed micromagnetic simulations in which DWs were inserted into a pair of parallel nanowires with dimensions as described previously. The magnetostatic interaction energy of the DWs was calculated as a function of *x*, the displacement of the upper wall from the centre of the lower wall. The simulated DWs had vortex (VW) structure as is expected from the thickness and width of the nanowires [12]. In these calculations the DW structure was approximated as being rigid.

Fig 1(a) shows the calculated interaction energy for DWs with opposite monopole moments in wires separated by 100 nm. The interaction energy increases with *x* due to the DWs' mutual attraction, and hence the upper DW perceives the influence of the lower DW as an energy well. Conversely, for DWs with like monopole moments [Fig 1(b)] the interaction energy decreases with the displacement of the upper wall and hence the upper DW perceives an energy barrier against propagation along the nanowire.

The magnetic field H_s required to stabilize a H2H wall against an energy gradient dE/dx can be calculated using the formula $H_s = \frac{1}{2\mu_0 M_s wt}\left(\frac{dE}{dx}\right)$ where w is the wire width and t is the wire thickness. Hence, by measuring the peak values of dE/dx from the curves shown in Fig. 1 we can predict the fields required for the upper DW to overcome the influence of the lower DW's magnetostatic field. Our calculations predict that an applied field of ±24 Oe would be required to release the upper domain wall from the potential well shown in Fig 1(a), while a field of ±23 Oe would be required to propagate the upper wall through the barrier shown in Fig 1(b). Because these depinning fields are comparable to typical DW propagation fields in nanowires (for example: [3,4,13]) it is likely that inter-DW interactions will have a substantial effect on the operation of DW-based devices.

In order to experimentally investigate these interaction effects we fabricated pairs of semicircular nanowires which curved either in the same direction ("concentric" geometry – inset Fig 2(a)) or opposite directions ("mirror" geometery – inset Fig 2(b)) to each other. Saturating and relaxing these nanowires along H_x (i.e. radially) placed the wires in bi-domain states such that DWs were present at both of the wires' apexes, in close proximity to each other. In the case of the "concentric" wires pairs of DWs with like monopole moments are formed, whereas for the "mirror" wires the walls have opposite monopole moments. In both geometries the right hand wire contains a lithographically patterned notch [14] to stabilize the DW position ("pinned" wall), while the DW in the left hand wire is free to move ("free" wall).

Fig. 2(a) shows an M-TXM image of the DW configuration formed in a pair of concentric wires with 150 nm edge-to-edge spacing following relaxation from negative saturation. The DWs both exhibit H2H character and vortex (VW) structure, but have opposite vortex chiralities. As expected, the DWs are initially repelled from each other such that the "free" DW in the left-hand wire is positioned slightly lower than the "pinned" DW in the right-hand wire. The fields required to overcome the pinning of the "free" DW in directions $+H_y$ and $-H_y$ were measured by slowly increasing the field along ±Hy. The sample was then saturated and relaxed in direction H_x between measurements to reinitialize the DWs. It was found that $H_y = (26 \pm 5)$ Oe was required to move the "free" DW up the wire and past the pinned DW, while only $H_y = (-6 \pm 6)$ Oe was required to move the "free" DW down the wire, thus demonstrating that the pinned DW creates an energy barrier against the propagation of the "free" DW.

Fig 2(a) also shows a plot of H_s against x, calculated from the energy landscape in Fig 1(b). Given the initial separation of the DWs this data predicts that a field of 20.8 Oe would be required to propagate the "free" DW through the energy barrier, a value slightly lower than that found experimentally. We suggest that this discrepancy is the result of additional pinning by small defects in the wires, which is

given credibility by the need to apply a small negative field to propagate the "free" DW down the wire in the experiment.

Additionally shown in Fig. 2(a) are predictions of H_s calculated using a simple monopole model which approximates the DWs' pole distributions to a single, central, point-monopole. Using this model the interaction energy assumes a Coulomb-like form $E_{m.p.} = \frac{q_i q_j}{4\pi\mu_0 r}$, where $q_i = \pm 2\mu_0 M_s wt$ is an analytically derived value of DW's net magnetic "charge" (+ H2H, - T2T) and r is the distance between the DWs. This model predicts a depinning field of 26.8 Oe, slightly higher than that derived from the micromagnetic model. This is to be expected as the finite pole distributions of the simulated DWs will smooth the energy gradients compared to those produced by the point-monopole model.

Fig. 2(b) shows example domain configurations, depinning fields and calculated values of H_s for a pair of mirror geometry wires with 100 nm edge-to-edge spacing. Now the left wire contains a H2H VW while the right contains a T2T VW. Hence, we expect the "free" DW in the left hand wire to be subject to a relatively symmetric energy well, and require fields of similar magnitude to propagate it up and down the wire. The experimentally measured (simulated) depinning fields were found to be 24 ± 5 Oe (24 Oe) in direction $+H_y$ and -35 ± 6 Oe (-24 Oe) in direction $-H_y$. The slight asymmetry and discrepancy with the simulated values is again attributed to small defects in the wires. As with the previous system the point-monopole model predicts a larger value of H_s than the micromagnetic data.

In Fig 2(c) we consider a mirror geometry wire pair with 50 nm edge-to-edge spacing. In these more closely separated wires transverse domain walls (TWs) are stabilized by the magnetic flux closing between the DWs [6,8]. Here, much higher depinning fields were measured (simulated) for the "free" wall than were measured in the cases of VWs: 108 ± 18 Oe (99 Oe) in direction $+H_y$ and -108 ± 10 Oe (-99 Oe) in direction $-H_y$. Furthermore, in contrast to the previous systems, the point-monopole model predicted much lower depinning fields (±39 Oe) than the micromagnetic simulations, indicating the influence higher order multi-pole terms in the DWs interaction. We suggest that the dominant effect here is dipole-dipole coupling between the TWs' transverse magnetization components [8].

To test this we added an additional dipolar coupling term, $E_{d.p.} = \frac{-\mu_0 m_y^{\ 2}}{4\pi r^5}\left(2y^2 - x^2\right)$ [15], to our simple monopole model, where x is the displacement of the "free" wall, y is the distance between the nanowire' centers, and $r^2 = x^2 + y^2$. $m_y = 6.2\times10^{-15}\,\mathrm{Am}^2$ represents the dipole moment of the DWs and was empirically fitted to give good agreement with the micromagnetic simulations. Fig. 2(c) shows a plot of H_s against x for both the simple monopole and monopole + dipole models. The model which includes the dipolar interactions agrees with the micromagnetically derived data much better than the simple monopole model, although the curve's peaks are a little shaper due to the point-dipole

approximation we use. More importantly, this model predicts a depinning field of 99 Oe, in excellent agreement with the micromagnetic data. Further investigations indicated that the monopole + dipole model predicts depinning fields to within 7% of micromagnetically derived values for edge-to-edge seperations between 50 nm and 200 nm.

In Fig. 3 we demonstrate the "capture" of a propagating DW by the magnetostatic interaction of a DW pinned in a neighboring nanowire. The geometry used for this measurement is shown in Fig 3(a). The semicircular wire contains a notch at its apex that is used to stabilize the position of the "pinned" DW, while a "free" DW is propagated through the "L" shaped wire.

The field sequence used to initiate the DW capture is as follows: initially the nanowires are saturated along $-H_x$ such that the "L" shaped wire is in a continuous configuration and the semicircular wire is in a bi-domain state with a H2H DW in the notch at position **C** (Fig. 3(i)). A $H_x = +1$ kOe field is then applied which causes a H2H DW to nucleate from the pad (**A**) and propagate to the corner of the L shaped wire, (**B**). The semicircular wire is also reversed so that a T2T DW is now pinned at **C** (Fig 3(ii)). The applied field is then gradually increased along $-H_y$, until at $H_y = 45$ Oe the "free" DW depins from **B** and propagates to **C** where it is captured by the energy well created by the pinned DW (Fig 3(iii)). The applied field is then further increased until at 65 Oe both walls depin, the "free" wall propagating in direction $-H_y$, the "pinned" wall in $+H_y$ (Fig 3(iv)).

Fig. 3 also shows M-TXM images of position **C** taken before the capture of the "free" DW, with only the "pinned" wall present (Fig. 3(b)), after the capture of the "free" DW (Fig. 3(c)) and after both DWs have depinned (Fig 3(d)). These clearly demonstrate that the interaction between two domain DWs is strong enough to capture a propagating wall and prevent its further motion.

In summary, we have investigated DW pinning induced by inter-DW magnetostatic interactions in pairs of planar magnetic nanowires. In contrast to previous studies [6,7] we have investigated DW pairs with both opposite and like monopole moments, demonstrating that the pinning potential takes the form of an energy well in the former case, and an energy barrier in the latter case. The applied fields required to overcome these potentials are significant when compared to typical DW propagation fields, and the interactions are strong enough to capture and prevent the further motion of a propagating DW. These results are of particular significance to the design of DW devices. We have also shown that pairs of transverse DWs interact significantly more strongly than vortex DWs, due to dipolar coupling between their magnetization structures.

Perhaps most importantly we have demonstrated that the effects of inter-DW interactions can be estimated to a reasonable degree using simple analytical models. Although the results of these models do not exactly reproduce those of more sophisticated micromagnetic simulations or experimental studies they will be an extremely useful tool for the design of experiments and devices in the future.

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Figure Captions

Fig. 1: Micromagnetically calculated domain wall interaction energies as a function of *x,* the displacement of the DW in the upper nanowire. (a) DWs have opposite monopole moments and clockwise vortex structure. The edge-to-edge separation of the nanowires is 100 nm. (b) DWs have like monopole moments, but opposite vortex chiralities. The edge-to-edge separation of the nanowires is 150 nm. In both cases the energy landscape perceived by the DW in the upper nanowire is illustrated schematically.

Fig. 2: M-TXM images of DW pairs in closely spaced nanowires. Scanning electron microscopy images of the imaged structures are shown as insets on the right. The magnetic fields required to displace the left-hand DW in directions Hy and –Hy are indicated on the images. The plots show calculated values of H_s against the displacement of the left-hand DW in direction +Hy. Data from three different models are presented: micromagnetic (closed circles), simple monopole (open circles) and monople + dipole (triangles). The dashed lines represent the peak values of H_s in the micromagnetic simulations, which are equivalent to the left-hand DWs' depinning fields. (a) DWs have vortex structure and opposite monopole moments. The nanowires edge-to-edge spacing is 100 nm. (b) DWs have vortex structure and lke monopole moments. The nanowires edge-to-edge spacing is 150 nm. (c) DWs have transverse structure and opposite monopole moments. The nanowires edge-to-edge spacing is 50 nm.

Fig 3. Capture of a propagating DW by a pinned DW. (a) Scanning electron microscopy image of the structure used in the measurements. An enlargement of region **C** is shown in the inset image. (i)-(iv) schematically show the magnetic field sequence applied, and how the system's magnetization responds. M-TXM images of region **C** are shown: (a) Prior to capture of the propagating DW (equivalent to (ii)). (b) After the capture of the propagating DW (equivalent to (iii)). (c) Following the field induced depinning of both DWs (equivalent to (iv)).

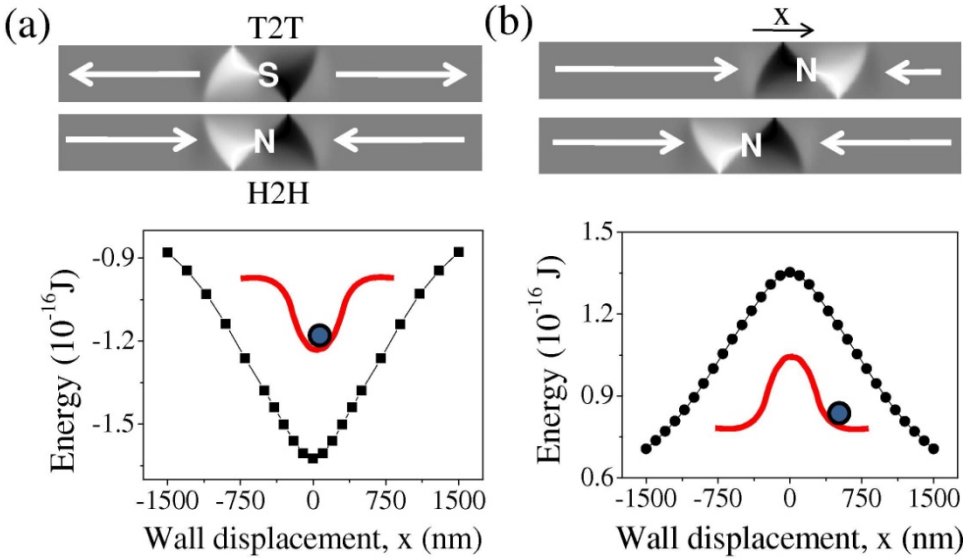
(a)
T2T
S
N
H2H
(b)
x
N
N
Energy (10^{-16}J)
-0.9
-1.2
-1.5
-1500 -750 0 750 1500
Wall displacement, x (nm)
Energy (10^{-16} J)
1.5
1.2
0.9
0.6
-1500 -750 0 750 1500
Wall displacement, x (nm)

Fig 1.

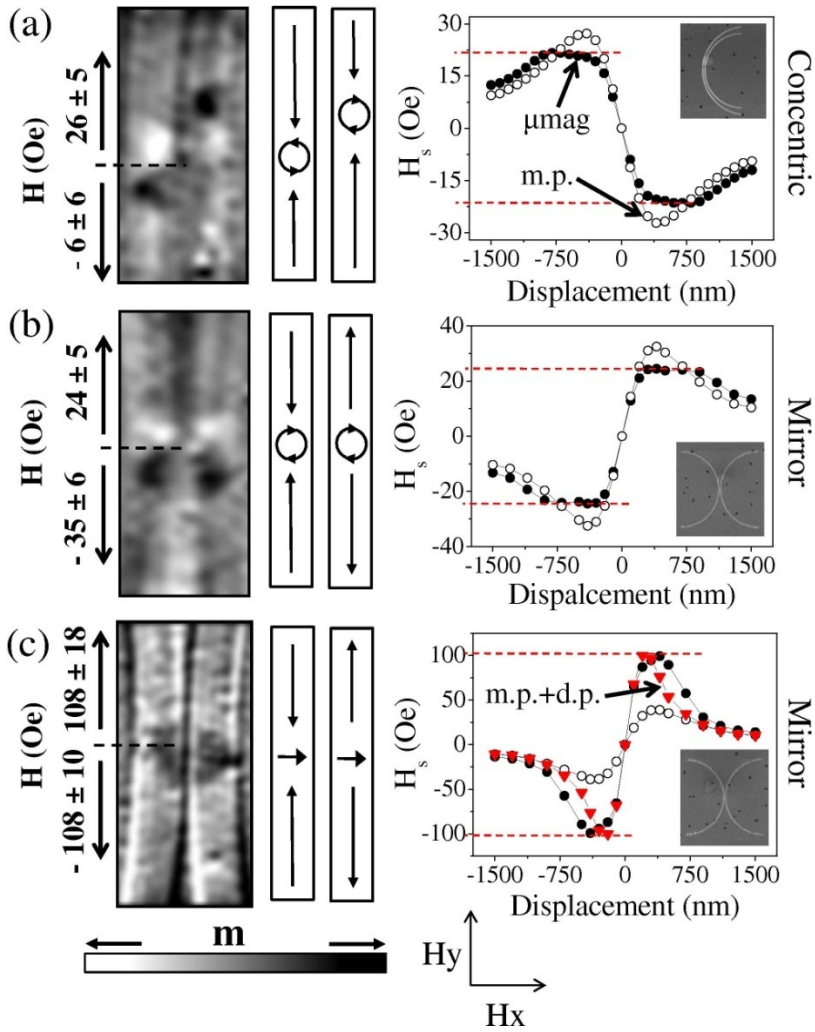
(a)
H (Oe)
26 ± 5
- 6 ± 6
H_s (Oe)
30
15
0
-15
-30
μmag
m.p.
-1500 -750 0 750 1500
Displacement (nm)
Concentric
(b)
H (Oe)
24 ± 5
- 35 ± 6
H_s (Oe)
40
20
0
-20
-40
-1500 -750 0 750 1500
Dispalcement (nm)
Mirror
(c)
H (Oe)
108 ± 18
- 108 ± 10
H_s (Oe)
100
50
0
-50
-100
m.p.+d.p.
-1500 -750 0 750 1500
Displacement (nm)
Mirror
m
Hy
Hx

Fig 2.

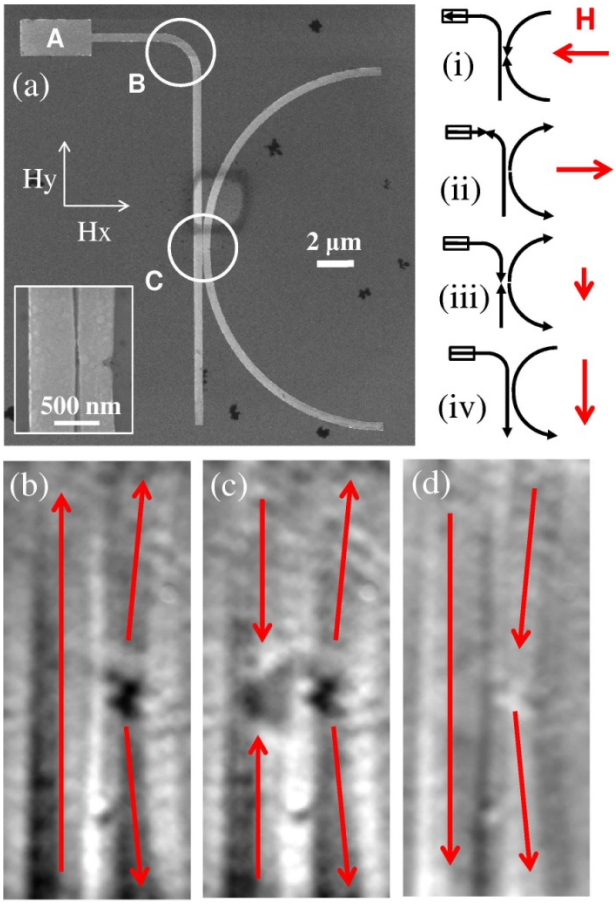

Fig 3.