Domain wall interactions at a cross-shaped vertex

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The interaction of two domain walls (DWs) at a cross-shaped vertex fabricated from two ferromagnetic nanowires has been experimentally investigated. Both magnetostatically repulsive and attractive interactions have been probed. It is found that in the repulsive case, a passing DW may directly induce the depinning of another that is already pinned at a vertex. This effect can be qualitatively described by considering only simple, magnetostatic-charge-based arguments. In the attractive case, however, asymmetric pinning is found, with complete suppression of depinning possible. This observed effect is contrary to simple charge-based arguments and highlights the need for full micromagnetic characterization of the DW interactions in more complex systems.

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1. Introduction

Artificial analogues to spin ice made of lithographically patterned, magnetic nanostructures offer an insight into ordering and excitations in frustrated systems. These systems combine the possibility of direct control over the governing geometrical parameters with relative ease in directly probing the system state [1]. Within spin-ice materials, magnetic monopolar excitations from the ground state have been predicted and received much interest [2–4]. With the ability to pattern large-scale arrays of nanoscale magnetic islands, artificial ice equally has been investigated for monopolar and elementary excitations, long-range ordering and correlation in both hexagonal and square lattices [5–7]. In addition to ordered nanomagnet arrays, connected networks of ferromagnetic nanowires have received attention [8] and are found to potentially offer fewer deviations from an ideal spin-ice analogue [9]. Within these networks, domain walls (DWs) mediate the movement of magnetostatic charge, and their interaction and pinning at vertices directly determines the overriding behaviour of the network.

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The controlled motion and interaction of DWs with patterned traps have equally been the subject of considerable investigation for possible future technological applications and the understanding of fundamental physical phenomena [10–13]. It is found that individual ferromagnetic nanowires may act as ideal conduits to a DW: a DW may be nucleated under the application of a large field, typically termed the nucleation field $H_N$, and then subsequently propagated over long distances under substantially lower field amplitudes (termed the propagation field, $H_P$), without the risk of further renucleation of new DWs. Furthermore, specific DW traps may be used to deliberately and accurately control the position and energy landscape experienced by a DW [14–17].

Within narrow, thin ferromagnetic nanowires, the transverse Néel DW (TDW) is energetically favourable [18,19]. These Néel DWs have a net divergence of magnetization ($\mathbf{M}$) and therefore carry a net magnetostatic charge $\pm Q_{DW} = \pm 2\mu_0 M_S S$, with the sign of the total charge reflecting whether the magnetization diverges in towards ($+Q_{DW}$, head-to-head, HH) or out from ($-Q_{DW}$, tail-to-tail, TT) the DW. Here, $M_S$ corresponds to the saturation magnetization and $S$ the cross-sectional area of the nanowire. Figure 1 shows micromagnetic simulations [20] of $\mathbf{M}$ within a HH TDW ($+Q_{DW}$; 100 nm wide, 10 nm thick nanowire) and the corresponding magnetostatic charge density distribution, defined as $\rho = -\mu_0 \nabla \cdot \mathbf{M}$ (4 x 4 x 5 nm$^3$ cell size, $M_S = 800$ kA m$^{-1}$, $A = 13$ pJ m$^{-1}$, $\alpha = 0.1$). Note that the DW has a highly asymmetric distribution of $\rho$ that extends over length scales similar to that of the nanowire width.

The interaction between DWs is of importance, as it governs the formation of the various topological defects in spin-ice analogue systems such as connected lattices and underlies their overall switching behaviour. Indeed, recent observations suggest repulsion between two DWs of equal charge may be associated with stabilizing ‘3 in’ excitations in hexagonal lattice arrays [21]. The DW–DW interaction in adjacent, unconnected nanowires has been probed, and is well described, considering the full magnetostatic charge distribution within the DWs [22,23]. When two DWs meet at a vertex, however, it is unknown how the additional DW energy contributions, e.g. due to exchange and finite DW deformation, will affect their interaction. It is also crucial to know the validity of simple models that consider the DW as a point source of magnetostatic charge in this interaction regime.

In this work, we investigate the interaction between two DWs in a cross-shaped vertex. The system is ideal for characterizing any interactions, as it is well understood for single DW–vertex interactions [24,25]. In probing each nanowire individually, two independent measurements of depinning from the interaction

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Figure 2. (a) SEM image of tested device showing the cross vertex formed from two perpendicular nanowires, one horizontal (H) and one vertical (V). Inset: two different corner shapes are tested, type I and II as shown. Scale bars, 200 nm. Using the two corner shapes, three different DW–DW interaction configurations can be initialized including: (b) repulsive equal charge case, (c) and (d) opposite charge attractive interactions. Note in (c) and (d), the two DWs reside in the vertex and create the ‘two-in, two-out’ state. In these cases, the sense of rotation of the state is set by the relative orientation of the internal $\mathbf{M}$ direction within the DWs and the order in which they enter the vertex. (Online version in colour.)

are measurable. Furthermore, the perpendicular geometry readily allows two persistent DWs to interact of any chosen net charge combination and sense of rotation. Presented are direct measurements of the repulsive ($+Q_{DW}, +Q_{DW}$) and attractive ($+Q_{DW}, -Q_{DW}$) interaction strengths. It is found that, while depinning behaviour in repulsive interactions may be qualitatively described by simple charge-based arguments, the behaviour of attractive interactions is more complex and requires consideration of all micromagnetic terms (including exchange energy and deformation of the DW internal charge distribution) to fully account for the observed asymmetries in the system.

2. Experimental procedure

Four-terminal cross-shaped vertices are investigated, allowing two DWs to controllably interact. Permalloy (Py) nanowire structures are fabricated on a Si substrate using electron beam lithography, thermal evaporation and a lift-off process. Wire cross-sectional dimensions are 100 nm wide and 10 nm thick, with $H_N \sim 210$ Oe and $H_P \sim 18$ Oe. Figure 2a shows an SEM micrograph of a typical structure. Two nanowires, one horizontal (H) and one vertical (V), intersect to form the cross-shaped vertex. At one end of each nanowire is a corner shape to allow the controlled nucleation of DWs with specific charge and internal rotation of magnetization, as has previously been demonstrated [26]. In this work, the
results from six devices (three of each corner shape type) are presented. The corners are placed in close proximity (approx. 500nm) to the cross shape to avoid unwanted transformations in the DW structure due to Walker breakdown during propagation [24,27]. Two types of corner shapes are used (I and II), as shown in the inset of figure 2a. A spatially uniform, globally applied magnetic field sequence, \( H(t) \), in the plane of the sample, is used to initialize DWs in these corners and subsequently propagate them towards the vertex. If an individual DW propagates along, for example, the \( H \) nanowire it will become pinned by the vertex. If its core direction is parallel to the direction of \( M \) in the \( V \) arm a potential well is experienced; a large potential barrier is experienced in the anti-parallel case [24,25]. In this way, it is possible to trap a single DW at the vertex, propagate a second DW in the perpendicular nanowire towards the vertex and cause the two to interact. Throughout the investigation, the structures tested are designed such that DWs meet a vertex in the parallel configuration, and so experience only a potential well.

As we choose two perpendicular nanowires, it should be noted that topologically the \( \pi \) rotation of \( M \) in each nanowire must remain regardless of the DW–DW interaction at the vertex. Therefore, interacting DWs cannot annihilate, even in an attractive \( +Q_{\text{DW}},-Q_{\text{DW}} \) case (see later).

The two corner shapes shown allow three configurations to be tested; shown in figure 2b–d are micromagnetic simulations of the expected two-DW states. Using corner shape I, an initializing field in the \((-1,-1)\) direction and a clockwise rotating \( H \), the configuration shown in figure 2b is initialized. The initializing field creates a HH DW in both the \( H \) and \( V \) corner shapes. From the rotating field, first the HH DW in the \( V \) arm \((+Q_{\text{DW}})\) is placed within the vertex. Then, subsequently, the HH DW nucleated in the \( H \) arm is propagated along towards the vertex, creating a repulsive \( +Q_{\text{DW}},+Q_{\text{DW}} \) interaction. Note that because the interaction is repulsive, the DW in the \( H \) arm remains outside the vertex despite a moderate field (10Oe) applied in the \(+x\) direction. Using the same corner shape, an initializing field in the \((-1,+1)\) direction and a rotating field allows an attractive interaction to be initialized (figure 2c); a HH DW \((Q_{\text{DW}})\) is created and propagated into the vertex in the \( H \) arm, with a TT DW \((-Q_{\text{DW}})\) initialized and subsequently propagated within the \( V \) arm. Owing to the magnetostatic attraction of the two DWs both reside at the centre of the vertex in equilibrium, creating the observed ‘two-in, two-out’ state shown. Finally, by using corner shape II and an initializing field \( H \) in the \((+1,-1)\) direction a HH and TT DW may be initialized in each corner shape, and the configuration shown in figure 2d subsequently created.

Once the chosen two-DW configuration is initialized, a constant field is applied along the \( y \)-direction, \( H_y \), in combination with a linearly increasing \( x \) field, \( H_x \). Switching of the long portions of the \( H \) and \( V \) nanowires are each probed separately using spatially resolved magneto-optical Kerr effect magnetometry. The characteristic field required to overcome the interaction and remove each DW from the initialized configurations, termed the depinning field \((H_D)\), may be found by observing switching of the nanowires as a function of both the applied field amplitude and direction.

Although in the presented experiments, \( H_y \) is the independent variable tested, for didactic purposes, \( H_x \) is plotted along the horizontal axis in all switching diagrams.

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3. Results

(a) Repulsive interactions: \(+Q_{DW}, +Q_{DW}\)

Before demonstrating repulsive DW interactions, we first briefly discuss single DW depinning from a cross vertex. Plotted in figure 3a as grey and black dashed lines are the depinning fields from a vertex for a single DW propagating in the \(H\) and \(V\) nanowire arms, respectively. The fields displayed are for a DW meeting the cross in the parallel configuration (i.e. \(M\) at the centre of the DW is parallel to the magnetization of the perpendicular cross arm). The field required to overcome pinning is approximately 94 Oe in the direction of propagation (i.e. \(x\) for the DW in the \(H\) arm, \(y\) for the DW in the \(V\) arm), with a positive field bias in the perpendicular direction linearly reducing this value.

We now examine the experimental depinning behaviour of two equally charged DWs from the vertex (as in the configuration of figure 2b). If we first examine figure 2b, for both the experimental and simulated cases, the \(H\) HH DW must traverse the vertex in which the \(V\) HH DW is pinned in order to switch the remaining portion of the \(H\) nanowire. Plotted as red circles in figure 3a, as a function of the applied field \(H_x\) and \(H_y\), is the experimentally obtained field.
required to achieve this and switch the remaining portion of the $H$ nanowire (shown for three separate structures). The three tested devices are represented as the three different symbols. No appreciable change is found in the DW depinning compared with single DW depinning (dashed line), suggesting the $H$ HH DW is unaffected by the presence of the $V$ HH DW in the vertex. In comparison, a considerable change is observed in the depinning behaviour of the $V$ DW compared with single DW pinning (black data in figure 3a). For large $H_y$ and moderate $H_x$ field values, switching remains as found in the individual DW case. However, for small $H_y$ and large $H_x$, the $V$ DW appears to be ejected from the cross at much lower $H_y$ fields than would normally be required. Comparing with depinning values obtained from micromagnetic simulations, as shown in figure 3b, qualitatively similar behaviour is observed: the $H$ DW appears unaffected by the presence of the $V$ DW, whereas the $V$ DW is ejected at considerably lower fields ($V$ DW depinning follows that of the $H$ DW above $H_x \sim 180$ Oe). Figure 3c shows images of the micromagnetic evolution of the configuration as the applied $H_y$ field is increased for the case of $H_y = 100$ Oe. They highlight the depinning behaviour of the DWs in the regime where $H_y$ is insufficient to allow depinning of an isolated $V$ DW. For moderate applied $H_x$ fields, the $H$ DW remains far from the vertex owing to the magnetostatic repulsion from the $V$ DW. As $H_x$ is increased, the $H$ DW moves towards the vertex increasing the magnetostatic energy between the two DWs. At the critical depinning field, the combination of the applied field and repulsion from the $H$ DW is sufficient to depin the $V$ DW. Now, in the absence of the $V$ DW, the $H$ DW is free to propagate through the vertex. In the simulations shown, the $H$ DW moves under fields greater than those required to overcome pinning of a DW in an empty vertex. As such, the $H$ DW passes straight through the cross and continues to propagate through the remaining $H$ nanowire. We can therefore conclude that as the $H$ DW approaches, the $V$ DW is ejected by the repulsive magnetostatic interaction and so the $H$ DW has directly induced depinning of the $V$ DW. Note that in the experimental results presented, the induced depinning of the $V$ DW occurs for lower $H_x$ fields than those required to depin an isolated $H$ DW. As such, following the induced depinning of the $V$ DW, the $H$ DW subsequently becomes trapped by the vertex and therefore follows the depinning characteristics of an isolated $H$ DW (grey dashed line in figure 3a).

(b) Attractive interactions: $+Q_{DW}, -Q_{DW}$

In the experimental structures tested, the corner shapes are placed in close proximity to the vertex and so no direct measurement of DW depinning in the $-x$ or $-y$ direction may be made. Examining figure 2c,d, however, we see the two attractive configurations are equivalent under a rotation about the $y$-axis. The sense of rotation of the magnetization of this state (producing either state in figure 2c or figure 2d) is governed by both the internal rotation of $M$ within the two DWs and also the order in which the DWs enter the vertex. By probing the depinning of the $H$ DW in the $+x$-direction for both initialized configurations, we may reconstruct the depinning phase diagram (in $H_x$ and $H_y$) for the $+Q_{DW}, -Q_{DW}$ system, i.e. by symmetry depinning in the $+x, \pm y$ for configuration of figure 2c is equivalent to depinning in the $-x, \pm y$ direction for configuration of figure 2d. In the following results and discussion, we will describe all depinning relative to the initial configuration of figure 2d.

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Figure 4. (a) Experimentally and (b) numerically obtained $H$ DW depinning field components for attractive DW–DW interaction (figure 2c). (c) Magnetostatic charge distribution within attractive $+Q_{\text{DW}}, -Q_{\text{DW}}$ interaction. Indicated by the red circle is the region of high charge and high exchange energy. (d) Example micromagnetic simulation images showing depinning mechanism in the attractive case. From the equilibrium configuration, considerable asymmetry is observed in forward ($+x$) compared with backwards ($-x$) depinning of the $H$ DW (see text for details). (Online version in colour.)

Shown in figure 4a is the experimentally obtained $x$ and $y$ components of the magnetic field required to overcome the attractive interaction and depin the $H$ DW from the initial ground state. As in the previous experiment, $H_y$ is fixed at a constant bias while the amplitude of $H_x$ is linearly increased. The individual devices tested are each represented as different symbols. We first observe that, in general, all pinning is stronger than for an individual DW in an empty vertex (see dashed lines in figure 4a). This would be expected, given that the attractive interaction acts to stabilize the configuration, making it energetically unfavourable to extract the DWs. Further to this, a large asymmetry is seen in the forward depinning ($+H_x$ applied) cases compared with backwards ($-H_x$ applied). In the $+x$-direction, pinning is, in general, sufficiently strong to prevent any forward propagation of the $H$ DW. Instead, reversal of the nanowire is associated with re-nucleation of a new DW in the nanowire ($\sim H_N$). In comparison, depinning in the $-x$-direction requires fields only slightly above single DW in an empty vertex pinning values (figure 3a). This behaviour is observed in all three tested structures and is in very good qualitative agreement with numerical simulations under similar experimental conditions (figure 4b). To explain this asymmetry, we examine the specific magnetostatic charge distribution of the HH–TT ($+Q_{\text{DW}}, -Q_{\text{DW}}$) initial state, as shown in figure 4c. It would be expected, considering only net magnetostatic charge, that the oppositely charged DWs
would create a zero charge density state. We see immediately, however, that regions of high charge density and therefore also high exchange energy remain, as highlighted. To transmit either of the DWs through the vertex into the +x- or +y-direction, i.e. apply $+H_x$ or $-H_y$ fields,\(^1\) these high exchange and charge areas must compress further and then traverse the vertex, dramatically increasing both the exchange and magnetostatic energy of the system. In comparison, DW motion in either the −x- or −y-direction relaxes the high charge areas, decreasing exchange. Depinning in these directions consequently requires only to overcome the magnetostatic attraction of the two DWs and any intrinsic pinning from the vertex. This process further explains any asymmetry in the effect of $\pm H_y$ bias field. A $-H_y$ field pushes the V DW further into the vertex—this compresses the magnetization together, increases exchange energy and so impedes passage of the H DW—whereas a $+H_y$ field will relax the configuration, making depinning of the H DW easier. The discontinuous drop in pinning field in the $+H_x, +H_y$ quadrant can be ascribed to removal of the V DW (in the $-y$-direction). Removal of this DW leaves only the single H DW in the vertex, which subsequently follows the single DW in an empty vertex depinning values. This jump directly demonstrates the effect V DW has on preventing forward (+x) propagation of the H DW.

Depinning field values for the V DW (not shown for clarity) are directly accessible only for $+H_y$ fields but are in strong agreement with the simultaneous reversal mechanisms of both H and V nanowires as described earlier: switching via renucleation in the $+H_x, -H_y$ quadrant and simultaneous depinning in $-H_x, -H_y$.

4. Discussion

Simple magnetostatic arguments would consider the DW purely as a mediator of net magnetostatic charge in the system and not take into account the internal distribution of $M$, nor the full micromagnetic behaviour of interacting DWs. In the presented repulsive DW–DW interaction, this description is sufficient to qualitatively describe the behaviour of the two DWs. The observed effects are therefore compatible with simple spin-ice analogies. Within this configuration, the repulsive interaction overwhelms the intrinsic pinning of the cross shape and highlights the difficulty in stabilizing a ‘four-in’ or ‘four-out’ vertex. In the attractive case, however, complete suppression of depinning can be observed and highly asymmetric behaviour is found, both of which are incompatible with simple magnetostatic arguments. Indeed, this behaviour cannot be accounted for by solely considering magnetostatic energy. Instead, only by fully considering the micromagnetic configurations of the DWs within the vertex, including their finite shape and exchange energy, is it possible to explain the behaviour observed.

As a simplification to the full micromagnetic configuration, it could be thought that the depinning within the $(+Q_{DW}, -Q_{DW})$ system may be accounted for by considering the effective composite $\pi$ DW across the diagonal of the vertex, which

\(^1\)A TT ($-Q_{DW}$) will move in the opposite direction to an applied field.
separates the two \( \mathbf{M} \) regions aligned in the \( 3\pi/2 \) and \( -\pi/2 \) directions. While this may be a valid description in wide nanowire geometries (\( \gg 100 \text{ nm} \)) where, in the absence of the highly confining vertex, exchange and demagnetizing restrictions are relaxed, we see clearly that the underlying symmetry for the investigated geometry cannot account for the \(+x\), \(-x\) asymmetry observed.\(^2\)

Figures 3 and 4 show little qualitative variation in behaviour between the tested devices. The largest variation in depinning field values measured was approximately \( \pm 25 \text{ Oe} \) (attractive interaction, \( H_y = -140 \text{ Oe} \), \( H_x \sim 110 \text{ Oe} \)) for the three devices tested. This would indicate that the resulting behaviour is relatively insensitive to nominal changes in wire geometry (the devices were nominally identical, with \( <10 \text{ nm} \) difference in wire width). However, the limited sample size prohibits a detailed investigation into the effect of wire cross-sectional area variation on the interaction. It is beyond the scope of this work to fully characterize these interactions in this way; however, figure 5 gives an insight into the general behaviour. Plotted is the depinning field, obtained from micromagnetic simulations, for the \((+Q_{\text{DW}}, -Q_{\text{DW}})\) interaction in both the \(+x\) and \(-x\) directions (\( H_y = 0 \text{ Oe} \)) as a function of wire width. In all cases, two TDWs are incident on the vertex, and a charge distribution qualitatively identical to figure 4c is initially obtained. It is seen that as wire width increases, the depinning field in both directions monotonically decreases. This would be expected given that in wider wires DWs may more easily distort in order to minimize energy and depin. Despite this, the relative asymmetry in depinning, here indicated by

\(^2\)Considering only the effective \( \pi \) DW would give ‘easy’ and ‘hard’ axes to depinning along directions parallel and perpendicular to the wall, respectively, i.e. depinning would be symmetric for the \((+H_x, +H_y)\) and \((-H_x, -H_y)\) quadrants (and equally \((-H_x, +H_y)\) and \((+H_x, -H_y)\)), which is clearly not observed.
the ratio of the depinning fields in each direction, remains relatively constant. This would indicate that, although changes in wire geometry modify the absolute values of the depinning fields, the overall qualitative behaviour is reproduced for a wide range of wire widths were TDWs are easily stabilized.

The results of figures 3 and 4 indicate that it is possible to interact and control the depinning (inducing or inhibiting) of one DW with another. This mechanism could be appealing for magnetic DW-based devices where information, encoded in the form of DWs, could be stored and manipulated solely using multiple interacting DWs.

The cross-shaped vertices investigated here allow two persistent DWs to interact. Crucially, even in the attractive case, a $\pi$ rotation of $\mathbf{M}$ must remain in each wire. A three-wire vertex (i.e. those found in hexagonal arrays) does not have this requirement, and so incident DWs may annihilate one another. In addition, the vertex itself is magnetostatically charged, and the DWs now no longer travel along what may be considered as independent wires. Only limited comparisons can therefore be made between the results shown here and the three-terminal case. Although much of the observed behaviour (i.e. induced depinning and a mutual blocking of propagation) is highly likely to also be observed under certain conditions in these vertices, further investigation is needed to characterize multiple DW interactions in these three-wire vertices.

The observed results highlight the care that must be taken in characterizing the interactions of DWs within a system, such as an artificial spin ice, to ensure that any ordering or possible asymmetries do not occur owing to interactions that do not have reciprocals in the analogous system, e.g. a true spin ice. The complexity of these interactions does, however, leave open the interesting question of how these effects manifest themselves in the switching behaviour of more complex networks such as square and hexagonal connected lattices.

5. Conclusions

In conclusion, the interaction of two DWs at a cross-shaped vertex has been experimentally investigated. Both repulsive HH–HH ($+Q_{DW}, +Q_{DW}$) and attractive HH–TT ($+Q_{DW}, -Q_{DW}$) have been probed. It is found that in the repulsive case, a passing DW may directly induce the depinning of another that is already pinned at a vertex. This effect can be qualitatively described considering only simple magnetostatic charge-based arguments. In the attractive case, however, asymmetric pinning is found, with complete suppression of depinning possible. This observed effect is contrary to simple charge-based arguments and highlights the need for full micromagnetic characterization of the DW interactions in more complex systems.

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