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Author
Bryan, M. T.

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Transverse Field-Induced Nucleation Pad Switching Modes During Domain Wall Injection

M. T. Bryan¹, P. W. Fry², T. Schrefl¹, M. R. J. Gibbs³, D. A. Allwood¹', M.-Y. Im³, P. Fischer³

¹ Department of Engineering Materials, University of Sheffield, Sheffield S1 3JD, United Kingdom
² Centre for Nanoscience and Technology, University of Sheffield, Sheffield S3 7H0, United Kingdom
³ LBNL/CXRO, 1 Cyclotron Road, Berkeley, California 94720, USA

Abstract

We have used magnetic transmission X-ray microscopy (M-TXM) to image in-field magnetization configurations of patterned Ni₈₀Fe₂₀ domain wall ‘injection pads’ and attached planar nanowires. Comparison with micromagnetic simulations suggests that the evolution of magnetic domains in rectangular injection pads depends on the relative orientation of closure domains in the remanent state. The magnetization reversal pathway is also altered by the inclusion of transverse magnetic fields. These different modes explain previous results of domain wall injection into nanowires. Even more striking was the observation of domain walls injecting halfway across the width of wider (>400 nm wide) wires but over wire lengths of several micrometers. These extended Néel walls can interact with adjacent nanowires and cause a switching in the side of the wire undergoing reversal as the domain wall continues to expand.

Introduction

Magnetization reversal in patterned ferromagnetic nanowires usually occurs via domain wall nucleation and propagation from one end (or both ends) of the wire.¹,² The switching of the nanowire can be significantly reduced if a large, magnetically soft pad is fabricated on one of the wire ends.³-⁵ These ‘nucleation pads’ reverse at lower fields than a typical isolated nanowire and go on to introduce a domain wall to the wire from the attached wire end. Domain walls nucleated in a pad often become pinned at the pad/wire junction,³,⁴,⁶,⁷ so cannot be introduced into the wire until a critical ‘injection’ field is reached. Once this occurs, the domain wall sweeps through the wire, reversing its magnetization. The injection field is designed to be lower than the nucleation field without a pad so that devices can be tested without unwanted domain wall nucleation, or device breakdown, occurring.⁸-¹⁰ Nucleation pads are, therefore, a simple and convenient way of introducing domain walls with a clearly defined propagation direction to sometimes complex devices at low fields. Carefully designed nucleation pads can also be used to control the chirality of injected vortex domain walls.¹¹ Nucleation pads vary widely in dimensions and shape, with squares, circles, ellipses, rectangles and several irregular shapes being investigated.³-⁵,¹¹,¹² More than one remanent magnetic domain configuration, or mode, can be observed within a pad after successive domain wall injections, with each mode resulting in a particular injection field.¹³

Injection pads are frequently used as part of nanowire devices and experimental structures. Magnetic-field-driven shift register memory can include an injection pad to write data¹⁴ while those attached to nanowire spiral turn sensors act as both a source and sink of domain walls.¹⁵ Both of these devices use two-dimensional wire circuits and therefore require the use of orthogonal in-plane magnetic fields to drive domain walls through wires of different orientations. These bi-axial fields
can significantly alter the fields at which domain wall injection occurs and control the number of
different injection modes that exist with attached wires of various widths.\textsuperscript{16} For narrower (< 320 nm)
wire\textsuperscript{17} fields, multi-modal behavior was observed in single-shot hysteresis loops as a stochastic variation of
axial injection fields between particular values. For wider (535 nm) wires, stepped magnetization
reversal was observed in single-shot hysteresis loops, although the reason for this remained unclear.

Here, we image the evolution of magnetic domains during field-driven reversal of injection
pads and observe the resulting domain wall injection in attached wires. Comparing the magnetic
configuration of the injection pads with micromagnetic models, we find that the relative orientation of
closure domains in the remanent magnetization configuration of injection pads determines the
reversal pathway that follows, although this is further affected by applied transverse fields. We also
find that domain walls can propagate down half the width of wider wires over a distance of several
micrometers, with one end of the wall travelling down the wire while the other end remains pinned
at the pad/wire junction.

Experimental

All structures were fabricated from thermally evaporated Ni\textsubscript{80}Fe\textsubscript{20} (permalloy) films
deposited on 100 nm thick Si\textsubscript{3}N\textsubscript{4} membranes using electron beam lithography followed by lift-off in
acetone held at 50°C. Samples must be at least 20 nm thick to ensure reasonable magnetization
contrast. We fabricated two sets of structures: set A structures were 24 nm thick and consisted of 2
\(\mu\)m \(\times\) 3 \(\mu\)m nucleation pads with wires of width 200 nm, 300 nm or 500 nm attached [Fig. 1(a)]. Set B
structures were 20 nm thick and consisted of 10 \(\mu\)m \(\times\) 10 \(\mu\)m nucleation pads with wires of width
400 nm or 700 nm attached [Fig. 1(b)]. At a distance of 10 \(\mu\)m from the nucleation pad, the set B
wires passed between two further orthogonal wires that were separated by 40 nm to the original
wire [Fig. 1(b)]. This feature was designed as part of a separate study into magnetostatic effects
upon domain wall propagation\textsuperscript{17} but some aspects of the behavior it induces are discussed here. The
diagrams in Fig. 1 define the orthogonal x and y directions, along which the fields \(H_x\) and \(H_y\) are
applied, respectively.

Magnetic transmission X-ray microscopy (M-TXM) was performed at beamline 6.1.2 at the
Center for X-ray Optics, Advanced Light Source in Berkely, CA.\textsuperscript{18} M-TXM uses the differential
absorption of polarized X-rays in magnetic materials due to X-ray magnetic circular dichroism to
create magnetization contrast in images. Fresnel zone plates are used as condenser and objective
lenses to provide up to 15 nm spatial resolution with an approximately 10 \(\mu\)m field of view, imaged
on an X-ray sensitive charge-coupled device (CCD) camera. The zone plates were also used to select
X-rays with either 707 or 853 eV photon energy in order to be sensitive to the Fe or Ni L\textsubscript{3}-edges,
respectively. Samples are held at an angle of 30° to the X-ray optical axis in order to provide
magnetization contrast in the x-direction. Electromagnets are used to apply fields \(H_x\) and \(H_y\) during
and between image capture. The signal-to-noise ratio of raw images is improved by averaging
several images from the CCD camera, binning adjacent CCD pixels and applying digital smoothing
functions. The images shown here are obtained by dividing two raw images obtained under different
field conditions to show changes in magnetization and remove the strong contrast between regions
containing magnetic structure and bare substrate. One of the raw images is often under remanent or
saturation conditions, so the final images represents the magnetization state of the second raw
image. Full details of the experimental arrangement of the microscope can be found elsewhere.\textsuperscript{19,20}

Micromagnetic simulations were performed using a hybrid finite element/boundary element
code\textsuperscript{21} developed by one of us to solve the Landau-Lifshitz-Gilbert equation of motion.\textsuperscript{22} This code
has been used previously to solve magnetization dynamics of domain walls in magnetic
nanowires\textsuperscript{23,24} and is well suited to the calculations required here. The magnetic elements were
designed with 20 nm thickness and discretized into a mesh of tetrahedral elements with a maximum
cell size of 20 nm. This is larger than the exchange length of Permalloy but modelling of large
nucleation pads required this to allow reasonable memory requirements and calculation times. Where domain walls propagation in wires was of interest, the maximum mesh size in wires was 5 nm laterally and 20 nm through the wire thickness. This asymmetric mesh results in much faster calculations for these thicknesses than a uniform 5 nm mesh size throughout and tests showed little variation between the two methods for the wires. The material properties of bulk permalloy were used in the model, with exchange stiffness \( A = 1.3 \times 10^{-12} \text{ J/m} \), saturation magnetization \( M_s = 800 \text{ kA/m} \), magneto-crystalline anisotropy \( K = 0 \text{ Jm}^2 \) and damping constant \( \alpha = 0.01 \). For simulations of switching fields, a linearly increasing magnetic field (1 Oe/ns) was applied parallel to the wire long axis. The structures were discretized using a tetrahedral mesh with a maximum cell width of 20 nm. The dimensions of the simulated structures mimicked the essential features of the experimental structures, although edge roughness was neglected from the model.

**Results and Discussion**

Figures 2 – 5 show M-TXM images of nucleation pads and 200 nm, 300 nm and 500 nm wide wires in sample set A under various \( H_x \) and \( H_y \). Note that \( H_x \geq 0 \text{ Oe} \) and \( H_y \leq 0 \text{ Oe} \) in figs. 2 and 3, but \( H_x \leq 0 \text{ Oe} \) and \( H_y \geq 0 \text{ Oe} \) in figs. 4 and 5; and figs. 3 and 4 show two nominally identical structures, not the same structure. In all the structures, the remanent magnetization state of the pad with no transverse field [part (a) of Figs. 2 – 5] consists of a uniform magnetization aligned with the wire axis, with closure domains at the edges facing and joining the wire. When \( H_x = 0 \text{ Oe} \) and \( H_y = 20 \text{ Oe} \), the magnetization state of the pad buckles, forming either eight [Figs. 2(b) and 5(b)] or six [Figs. 3(b) and 4(b)] domains, half of which have magnetizations rotated away from the x-axis. As \( H_x \) is increased, the rotation of the domains become larger and the non-rotated domains shrink [Figs. 2(a)-(d), 3(a)-(d), 4(a)-(d) and 5(a)-(d)]. By \( |H_x| = 100 \text{ Oe} \) (125 Oe for the 500 nm wide wire), the magnetization in each pad is aligned with the field, and a domain wall is either left at the junction with the wire [Figs. 2(e) and 3(e)], or injected into the wire [Figs. 4(e) and 5(e)].

When a transverse field is applied in addition to the axial field, more complex modes of magnetization reversal are seen in the pad. In the pad with the 200 nm wide wire under \( H_x = -12 \text{ Oe} \) [Figs. 2(f)-(j)], the magnetization enters a six-domain state when \( H_x \leq 20 \text{ Oe} \) [Fig. 2(f) and (g)], but changes into a four-domain state at \( H_x = 40 \text{ Oe} \) [Fig. 2(h) and (i)], before the pad completes magnetization reversal at \( H_x \approx 100 \text{ Oe} \) [Fig. 2(j)]. The magnetization states of the pads with 300 nm wide wires under a transverse field [Figs. 3(f)-(j) and 4(f)-(j)] appear to be distorted forms of the magnetization state with no transverse field when \( |H_x| \leq 40 \text{ Oe} \). However, these low field distortions are complements of each other: in one pad wire closure domains are expanded and the central domain is reduced [Figs. 3(f)-(h)], whereas in the other wire the closure domains are reduced and the central domain is expanded [Figs. 4(f)-(h)]. These distortions precede differences in the ongoing evolution of magnetization, with the former pad undergoing almost complete reversal between \( |H_x| = 80 - 100 \text{ Oe} \) [Figs. 3(i) and (j)] while the latter forms a Landau pattern, or vortex, at \( |H_x| = -80 \text{ Oe} \) [Fig. 4(i)] that is expelled at higher fields to complete the magnetization reversal [Fig. 4(j)]. The pad with a 500 nm wide wire under \( H_x = 9 \text{ Oe} \) forms a six-domain state when \( |H_x| \leq 20 \text{ Oe} \) [Figs. 5(f) and (g)], but this changes to a vortex state at higher fields [Figs. 5(h) and (i)]. The vortex is gradually driven out of the pad as \( H_x \) is increased, until a uniform magnetization state is reached at \( |H_x| = 125 \text{ Oe} \) [Fig. 5(j)].

While we have not studied the effect of wire width on the magnetization state of the pad comprehensively, similar magnetization states were observed in pads with different width wires attached. For example, figures 2(b) and 5(b) show similar magnetization configurations in pads with 200 nm and 500 nm wide wires attached, respectively, while figures 2(f)-(j) and 3(f)-(j), and figures 4(f)-(j) and 5(f)-(j) each show very similar magnetization reversal pathways under transverse fields.
This suggests that the different magnetization states seen are alternative modes of pad reversal that are independent of the wire width, rather than an effect of the wire width on the shape anisotropy at the pad-wire junction. This stochastic behaviour has been previously observed in pads,\textsuperscript{13} where the number of modes present was temperature-dependent.

Although the transverse field affects the mode of reversal in the pad, ultimately the pad reaches a single-domain magnetization before a domain wall is injected into the wire [part (j) of figs. 2 - 5]. Nevertheless, the transverse field does appear to influence domain wall injection. For example, the 500 nm wide wire switched at $H_y = -125$ Oe without a transverse field, but at $H_y = -130$ Oe when $H_x = 9$ Oe. This increase in domain wall injection field resulting from the inclusion of transverse fields contrasts with our previous results from pads and wires of different dimensions.\textsuperscript{16} This indicates that the detailed effect of transverse field is likely to depend on the particular pad/wire geometry and dimensions employed and does not follow a generic rule.

However, we have been able to understand the pathway of pad magnetization more generally by using micromagnetic simulations. Figure 6 shows simulated magnetization structures of a 2 $\mu$m x 3 $\mu$m x 20 nm Ni$_{80}$Fe$_{20}$ pad with a 500 nm wide wire attached under fields $H_x = 15$ Oe and $H_y = 0$ Oe and $\pm 10$ Oe. Two initial configurations are shown, with the closure domain on the left-hand edge of the pad either parallel [fig. 6(a)] or anti-parallel [fig. 6(b)] to both closure domains on the right-hand edges of the pad. A third configuration was also modelled, with the closure domains on the right-hand edge opposing each other, but this had a higher energy than the other two configurations and behaved in a similar way to that shown fig. 6(b), so will be neglected from the following analysis. The alignment of the closure domains determines the number of domains that form within the pad. Where all the closure domains are aligned [fig. 6(a)ii], the simulations accurately reproduce the six-domain magnetization patterns seen experimentally with the 300 nm wide wires and no transverse field [figs. 3(b) and 4(b)]. Comparison of the M-TXM images and the micromagnetic modelling suggests that magnetization states that occur in the pads with the 300 nm wide wires under a transverse field [figs. 3(g) and 4(g)] have closure domains that are aligned. The ensuing magnetization reversal pathways differ because the transverse field is parallel to the closure domains in fig. 3(g) [similar to fig. 6(a)i] and anti-parallel to the closure domains in fig. 4(g) [similar to fig. 6(a)iii]. In the absence of a transverse field, an eight-domain magnetization state in the pads is predicted by the models when the closure domains on the right-hand edges are both anti-parallel to the closure domain on the left-hand edge [fig. 6(b)iii]. This is similar to those seen experimentally in figs. 2(b) and 5(b). Under $H_y = -10$ Oe [fig. 6(b)iii], the domains rotate to form a state similar to those observed in figs. 2(g) and 5(g). We can predict, therefore, that the magnetization reversal pathway in square or rectangular nucleation pads depends primarily on the relative orientation of closure domains. In our M-TXM experiments, the transverse fields were only applied after remanence. Our previous experiments\textsuperscript{16} used a continuously rotating magnetic field. For domain wall injection into narrow wires, bi-modal behavior tended to cease as the transverse field component increased. It is now clear that this may have been due to the transverse field aligning opposite closure domains, thus dictating the subsequent magnetization reversal pathway.

As $H_x$ was increased in the calculations to inject a domain wall, the pad magnetization states changed from those shown in fig. 6 to vortex states, as observed by M-TXM in pads with a 500 nm wide wire attached [fig. 5(h)]. At higher fields, the magnetization of the modelled pad became single-domain, although closure domains remained at fields up to $H_y = 90$ Oe. Different injection fields were observed with pads of different initial closure domain configurations when no transverse field was applied. Pads initially magnetized with parallel closure domains injected domain walls at $H_x = 59$ Oe, 45 Oe or 44 Oe when $H_y = 10$ Oe, 0 Oe or -10 Oe, respectively. By contrast, when the closure domains of the pad were anti-parallel, domain walls were injected at $H_y = 56$ Oe, 56 Oe or 54 Oe while $H_y = 10$ Oe, 0 Oe or -10 Oe, respectively. The increase in injection field for the parallel case when $H_y = 10$ Oe was brought about by a reversal in the closure domain configuration so that, at the
point of injection, they had become anti-parallel. This supports the suggestion that experimentally observed multi-modal injection is due to the magnetization state of the pad.

Observation of domain wall injection into wires in sample set B provided some surprising results. Figure 7 shows a sequence of images of a nucleation pad and part of a 700 nm wide wire under increasing axial field, \( H_x \). Upon reaching \( H_x = 70 \) Oe, a domain wall enters the wire. However, the injection is anything but uniform; the domain wall travels for approximately 1.8 \( \mu m \) down the lower half of the wire only whereas across the top half of the wire the domain wall remains pinned at the wire/pad junction [Fig. 7(a)]. As \( H_x \) is increased, the domain wall extends progressively further into the wire [Fig. 7(b) and (c)], reaching a distance of 4.5 \( \mu m \) from the pad when \( H_x = 120 \) Oe. Throughout this, the domain wall retains some 90° turns close to the pad and terminates at the upper join between the wire and pad. The domain wall is finally injected across the whole wire when \( H_x = 130 \) Oe. Similar observations were made with domain wall injection into 400 nm wide wires as part of sample set B.

Domain walls in nanowires usually remain confined to a small region and are therefore categorized as ‘head-to-head’ (or ‘tail-to-tail’) structures, with magnetization in the wall rotating in-plane for relaxed walls. Domain walls pinned at a notch on one side of a wire have recently been observed to extend over a length of approximately 1.5 \( \mu m \) but the walls essentially retain a head-to-head structure. This description does not fit the extended wall seen in Fig. 7. Rather, it has a head-to-head structure only where it is orthogonal to the wire length [Fig. 7(e)]. The extended regions lying parallel to the wire instead have a domain configuration either side of the wire more akin to a Bloch or Néel type wall [Fig. 7(e)].

We also moved further along the 700 nm wide wire, away from the nucleation pad, in order to observe how the extended Néel wall interacted with the orthogonal wires present in sample set B. The two ‘free’ wires had previously been saturated in the +y-direction [see Fig. 8(a) for definition of directions]. Figure 8(a) shows an extended domain wall approaching the wire cross (\( H_x = 70 \) Oe), reaching 10 \( \mu m \) from the pad. Figure 8(b)-(d) are from a separate sequence of fields but show that at higher applied fields (\( H_x = 110 \) Oe), the domain wall reaches the wire cross [Fig. 8(b)]. However, rather becoming pinned at this point, the stray magnetic field from the ends of the orthogonal wires appears to cause the domain extending into the wire to locally expand across the wire width. The domain had continued to expand beyond the cross, reverting back to expansion through half the wire width only. However, now the domain expansion appears on the opposite side of the wire than previously. As the field is increased further, the wire beyond the cross undergoes full magnetization reversal [Fig. 8(c); \( H_x = 120 \) Oe] before the wire between the pad and the cross finally switches completely [Fig. 8(d); \( H_x = 130 \) Oe].

Figure 9 shows micromagnetic simulations of a NiFeFe_{20} 20 nm thick patterned element in which a domain wall is being injected from a 4 \( \mu m \times 4 \) \( \mu m \) nucleation pad into a 400 nm wide wire under an applied axial field of 60 Oe. While the lower part of the domain wall extends into the nanowire for several micrometers, the upper part remains pinned at the pad/wire junction. This asymmetry is due to the closure domains in the pad above and below the junction with the wire having opposite orientations in the initialized structure before the field was applied. Such end domains are not visible in Fig 7 but such an interaction is most likely to be the cause of the strong domain wall pinning observed. The domain wall is also observed to have a Néel-type configuration along the wire length. In order to achieve the extended domain wall structure in the calculations we had to reduce the exchange stiffness to \( A = 2.6 \times 10^{-12} \) J.m\(^{-1}\) since using the more commonly accepted value of \( A = 1.3 \times 10^{-13} \) J.m\(^{-1}\) resulting in domain walls only extending for 650 nm into the wire. Reduced values of exchange stiffness compared with those in bulk have previously been used when describing magnetic configurations in thin films and patterned elements. We have estimated the energy of the extended domain walls by performing micromagnetic simulations of a
domain wall initialized down the centre of 400 nm wide, 20 nm thick Ni_{80}Fe_{20} rectangular elements of 2 – 4 μm length [Fig. 9(c)]. For all wire length, the wall relaxed to a Néel-type configuration and the end domains appeared very similar. The total calculated energy increased linearly with wire length, allowing us to estimate the domain wall energy density as γ = 3.0 mJ.m^{-2}. The domain wall extended to a length of 10 μm in Fig. 8 therefore has an energy = 0.6 fJ and we can assume that the interaction energy between the domain wall and the closure domain in the nucleation pad is of at least this value. The modelled domain walls such as in Fig. 9(c) also allow us to estimate a domain wall width of 40 nm by extrapolating the magnetization gradient at the center of the domain wall. [NB: these calculations currently use a value of A = 1.3 × 10^{-12} J/m but we are re-calculating for the paper with the lower exchange stiffness]

While the extended Néel wall may be unexpected, it does explain our previous observation of stepped hysteresis loops when domain walls were injected from nucleation pads into 500 nm wide wires. This was observed even within single magnetization reversal events, ruling out the simple possibility of stochastic variation in single-step switching field. What now appears to have been happening is injection of a domain across half of the wire width at a low field with subsequent reversal of the other half at a higher field, as observed here. While we do not claim that the extended Néel walls are necessarily typical of domain wall behavior in wires, the trend to wider and thicker wires to promote head-to-head walls with a vortex spin structure may result in further similar observations being made. The interaction of the extended wall with the magnetostatic cross [Fig. 8] indicates that the head-to-head/Néel hybrid walls will exhibit unusual behavior in what might otherwise be a well understood magnetic nanowire system, perhaps affecting device performance.

Conclusion

We have used magnetic transmission X-ray microscopy (M-TXM) to image the evolution of magnetization configurations in patterned Ni_{80}Fe_{20} rectangular nucleation pads and attached wires during domain wall injection. The relative orientation of closure domains in the pads determines the magnetization reversal pathway under an axial field. However, the addition of transverse fields can alter these and lead to the pads undergoing reversal under lower axial fields. Domain wall injection into wider (400 and 700 nm) wires is observed to often take place initially across one half of the wire width only, resulting in a domain wall with large regions of Néel-type structure. This behavior has wider implications for experiments and devices using patterned magnetic wires with larger cross-sectional dimensions.

Acknowledgements

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References


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Figure Captions

Figure 1  Schematic diagrams of (a) set A and (b) set B Ni$_{80}$Fe$_{20}$ structures, each comprising a nucleation pad and attached wire. Set A wires have width $w = 200$ nm, 300 nm or 500 nm and a 180° arc of radius, $r = 2 \mu m$ when $w = 200$ nm or 300 nm, and $r = 4 \mu m$ when $w = 500$ $\mu m$. Set B has $w = 400$ nm or 700 nm. The free wires in set B structures are separated from the main wire by $d = 50$ nm ($w = 400$ nm) or $d = 100$ nm ($w = 700$ nm).

Figure 2  M-TXM images showing the magnetization state of a 3 $\mu m \times 2 \mu m$ nucleation pad with a wire attached of width, $w$, 200 nm. $H_1$ and $H_y$ are applied as shown. The schematics are a guide to aid interpretation of the images. The images were obtained by using 707 eV photons and by comparing raw images for the fields shown with one of saturation under $H_x = -500$ Oe.

Figure 3  M-TXM images showing the magnetization state of a 3 $\mu m \times 2 \mu m$ nucleation pad with a wire attached of width, $w$, 300 nm. $H_1$ and $H_y$ are applied as shown. The schematics are a
guide to aid interpretation of the images. The images were obtained by using 707 eV photons and by comparing raw images for the fields shown with one of saturation under \( H_x = -500 \) Oe.

**Figure 4** M-TXM images showing the magnetization state of a 3 \( \mu \)m x 2 \( \mu \)m nucleation pad with a wire of width, \( w \), 300 nm. \( H_x \) and \( H_y \) are applied as indicated. The schematics are a guide to aid interpretation of the images. The images were obtained by using 707 eV photons and by comparing raw images for the fields shown with one of saturation under \( H_x = 500 \) Oe.

**Figure 5** M-TXM images showing the magnetization state of a 3 \( \mu \)m x 2 \( \mu \)m nucleation pad with a wire of width, \( w \), 500 nm. \( H_x \) and \( H_y \) are applied as indicated. The schematics are a guide to aid interpretation of the images. The images were obtained by using 707 eV photons and by comparing raw images for the fields shown with one of saturation under \( H_x = 500 \) Oe.

**Figure 6** Micromagnetic simulations of a 2 \( \mu \)m x 3 \( \mu \)m x 20 nm Permalloy pad attached to a 500 nm wide wire. The closure domains on the right-hand side of the pad are (a) parallel or (b) anti-parallel to the left-hand closure domain. In each case, \( H_x = 15 \) Oe and \( H_y = (i) 10 \) Oe, (ii) 0 Oe and (iii) -10 Oe.

**Figure 7** M-TXM images of domain wall injection into a 700 nm wide wire under \( H_x \) = (a) 70 Oe, (b) 100 Oe, (c) 120 Oe, and (d) 130 Oe. The images were obtained using 853 eV X-rays and by comparing raw images for the fields shown with remanence \( (H_x = 0 \) Oe). (e) Schematic diagram of magnetization configuration (arrows) of a partially-injected domain wall in a magnetic nanowire attached to a nucleation pad.

**Figure 8** M-TXM images of domain wall propagation through a magnetostatic wire cross under \( H_x \) = (a) 70 Oe, (b) 110 Oe, (c) 120 Oe, and (d) 130 Oe. Note that (a) was obtained from a separate sequence from the other images. The images were obtained using 853 eV X-rays and by comparing raw images for the fields shown with remanence \( (H_x = 0 \) Oe).

**Figure 9** (a) full model and (b) expanded view of pad/wire junction. Some more details of mesh sizes and anything else. Colour scale. What the arrows represent. (c) Simulation of a relaxed domain wall along the length of a X \( \mu \)m long, 400 nm wide, 20 nm thick Ni_{80}Fe_{20} element.
Figure 1

Figure 2
Figure 3

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Figure 9