Spatially resolved observation of domain-wall propagation in a submicron ferromagnetic NOT-gate

Xiaobin Zhu[a)]
Department of Physics, McGill University, Montreal, Quebec, H3A 2T8, Canada

Dan A. Allwood
Department of Engineering Materials, University of Sheffield, Sheffield S1 3JD, United Kingdom

Gang Xiong and Russell P. Cowburn
Department of Physics, Imperial College London, Prince Consort Road, London SW7 2BW, United Kingdom

Peter Grütter
Department of Physics, McGill University, Montreal, Quebec, H3A 2T8, Canada

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Domain-wall propagation under an external magnetic field in a submicron ferromagnetic ring integrated with a NOT-junction is investigated by magnetic force microscopy and micromagnetic modeling. Within a certain magnetic field range, one head-to-head or tail-to-tail domain wall propagates in the structure. Magnetic fields above this range cause nucleation of additional domain walls in the ring structure while fields below this range are not able to switch the NOT-junction magnetization. This explicitly demonstrates the magnetization reversal, operation, and failure modes of a magnetic NOT-junction. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2009050]

In planar magnetic wires with submicron width, the magnetization tends to lie parallel to the wire to minimize energy. Domain walls form where opposite magnetization directions meet and can be defined by the polarity of the adjacent wire magnetization directions as either *head-to-head* or *tail-to-tail* domain walls.[1] Domain walls can propagate with very high velocities (1 km/s) under moderate magnetic fields applied along the wire length.[2,3] By incorporating a cusp structure in magnetic wire rings, information processing has been demonstrated by domain-wall propagation with the cusp structure acting as a logical NOT gate.[4,5] These experiments were conducted by monitoring the magnetization at a fixed location using magneto-optic Kerr effect measurements.[6] The operating principle of the magnetic NOT gate is that under an in-plane rotating magnetic field, a domain wall passes through the NOT junction, to leave opposite "input" and "output" magnetization directions. In this letter, we report the spatially resolved observation of this magnetic device by magnetic force microscopy (MFM). We not only observe the domain-wall propagation, but also elucidate the switching process in the cusp area.

The magnetic structure was fabricated by focused ion beam (FIB) milling of a 5 nm thick thermally evaporated Permalloy ($Ni_{80}Fe_{20}$) film using 30 keV Ga^{+} ions (see Ref. 4 for details). The structure is identical to that in Ref. 4, consisting of a continuous ferromagnetic wire rectangular ring with a cusp along one of the rectangle edges [Fig. 1(a)]. The wire width throughout the structure is 200 nm. Fabrication by FIB milling will lead to the incorporation of Ga close to the wire edges, but it is unclear exactly how this will affect domain-wall propagation. MFM using low magnetic moment tips (30 nm CoPtCr) was operated in the constant height mode with the tip-sample distance between 100 to 150 nm.[7] With smaller tip-sample separation, the image contrast and spatial resolution are better but we find that the domain walls are sometimes dragged or pushed away by the stray field emitted from the MFM tip. To resolve the weak signal as a result of using large tip-sample separation, the measurements were performed in a vacuum (2×10^{-5} Torr) to reduce cantilever damping and thus increase sensitivity. The silicon cantilever had a spring constant of 1 N/m, a resonance frequency of 74 kHz, and a Q factor under a vacuum of 50 000.

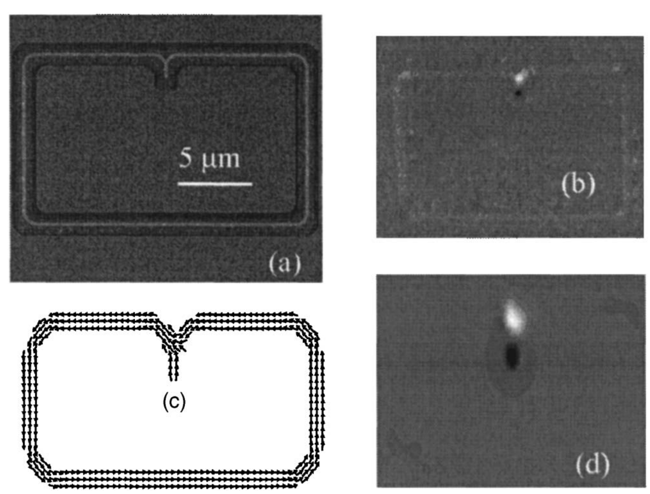

FIG. 1. Permalloy ring structure with an integrated NOT gate and its magnetic structures. (a) Secondary electron image from FIB irradiation of a structure identical to that investigated here. (b) MFM image of the ring structure in its initialized state. No domain structure is observed except the wire junction and stub. Here, the black and white spot depend upon the magnetization orientation in these regions. (c) Simulated magnetization of 3.85 μm $\times$ 1.95 μm structure in the initialized state. (d) Out-of-plane component of the stray field calculated for the initialized state based on the magnetization configuration shown in (c). Gray scale is used. The black shows the negative stray field, and the white shows the positive stray field.

[a)]Author to whom correspondence should be addressed at: Avadh Bhatia Physics Laboratory, University of Alberta, Edmonton, Alberta T6G 2J1, Canada; electronic mail: xzhu@phys.ualberta.ca

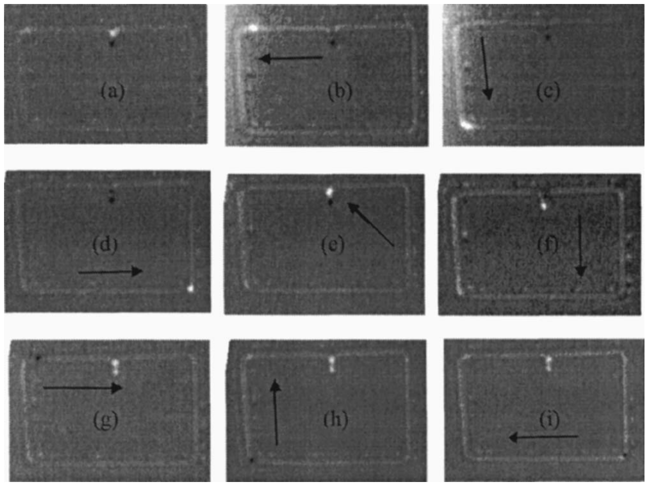

FIG. 2. MFM images at remanence after applying a 100 Oe magnetic field in orientations indicated by the black arrows. The contrast in the cusp can be black-black, white-white, black-white, or white-black, depending on the magnetization configuration. Other black or white spots in the images are due to a head-to-head or tail-to-tail domain wall.

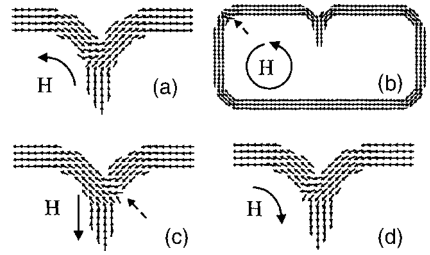

FIG. 3. Simulation results of the structure. (a) Magnified view of the cusp region in Fig. 1(a), with the structure in its initialized state. These is a head-to-head domain wall between one wire and the junction region, while the stub is magnetized in one direction. A magnetic field must be applied in the direction indicated by the large arrow in order to move the domain wall. (b) Magnetic configuration of the entire structure after application of the field indicated in (a). (c) Magnified view of the cusp region after one cycle of magnetic field has been applied. The domain wall is now on the opposite end of the junction than seen in (a). A magnetic field of at least 50 Oe must be applied in the direction indicated by the large arrow in order to switch the stub. (d) Magnified view of the cusp region after the stub magnetization has been reversed. The magnetization of the structure is now opposite to that of (a) in all positions. Furthermore, the magnetic field required to continue the clockwise propagation of the wall around the structure is now opposite to the direction in (a).

The weak frequency change during measurement is monitored by a digital phase locked loop from NanoSurf.[8]

Figure 1(b) shows an MFM image of the magnetic structure in its initialized state. The magnetization is continuous throughout the ring, resulting in there being no internal domain walls except in the cusp area, due to its inversion function. Here, there is one black and one white region, corresponding to a repulsive and attractive interaction with the MFM tip, respectively.

To interpret this image, we performed a micromagnetic simulation[9] of a cusp structure within a ring measuring 3.85 μm $\times$ 1.95 μm. A larger ring was used experimentally in the original studies[4] purely to allow a 5 μm diameter laser spot to probe the wire magnetization. The smaller ring size used in the micromagnetic simulations will not affect the overall magnetic behavior. The cusp dimensions, wire width, and wire thickness are identical in the simulation and experiment. Figure 1(c) shows the simulation result, with arrows to indicate the orientation of magnetization. The only domain wall that is present is a head-to-head domain wall in the wire junction region. The magnetization in the stub region of the cusp is oriented along the stub length, similar to the magnetization state of an elongated isolated bar. The out-of-plane component of the stray field at the unconnected end of the stray stub above the ring plane depends on the orientation of the magnetization in the stub. Figure 1(d) shows the out-of-plane stray field at 100 nm above the sample plane for the magnetization configuration in Fig. 1(c). The white shows the positive stray field, and the black shows the negative stray field. Assuming that the out-of-plane stray field from the MFM tip is positive, the tip would experience an attractive force above the head-to-head domain wall and a repulsive force above the unconnected end of the stub. This picture from the simulated stray field configuration is consistent with our experimental observations discussed above [Fig. 1(b)]. Out-of-plane stray field distributions from the ring structure can therefore be used to interpret MFM images, as the MFM image is usually a combined effect of the sample's stray field and stray field gradient. Note that the contrast from the whole nanowire is observed experimentally [Fig. 1(b)] but not in the simulation [Fig. 1(d)]. In MFM experiments on magnetically soft materials, a generally attractive background interaction is measured due to the MFM-tip stray field inducing weak, local rotations of the sample magnetization. This is in contrast to simulations, where the magnetization of the ring is always perfectly aligned normal to the tip. Our simulation results confirm that the domain wall in this case is a transverse wall, although this is not necessarily true for wires of different width and thickness.[10]

We applied quasi-static magnetic fields of 100 Oe to the magnetic structure in various in-plane directions, as indicated in Fig. 2. After each application and removal of magnetic field, an MFM image was obtained. Figure 2(a) shows the same initialized magnetization state as Fig. 1(b). After a field is applied in the direction indicated in Fig. 2(b), the white spot in the MFM image has moved from the cusp region to a corner in the ring structure due to field-induced propagation of the head-to-head domain wall. The domain wall cannot propagate any further than this corner due to the applied magnetic field being oriented parallel to the ring section between the cusp and this first corner. The junction area is now represented by two black regions, something that we will explain later. Additional magnetic fields propagate the domain wall around the ring and back to the other side of the cusp region [Figs. 2(c)–2(e)]. At this input to the cusp, the domain wall must overcome pinning in order to propagate further. For this to occur, a magnetic field of more than 50 Oe must be applied parallel to the stub length. Once this has been achieved [Fig. 2(f)], the initialized magnetization state is again observed but now with a reversed stray field contrast (black spot above white spot). This is due to the stub magnetization being reversed and the inversion function of the cusp junction causing the head-to-head wall to become a tail-to-tail domain wall. With this inversion of adjacent magnetizations, the tail-to-tail domain wall (black dot) appears to propagate in the opposite direction to an applied magnetic field [Figs. 2(g)–2(i)].

In order to help explain the experimental observations, Fig. 3 shows micromagnetic simulations at remanence after a magnetic field has been applied in a particular direction, as indicated. Figure 3(a) shows a magnified view of the cusp

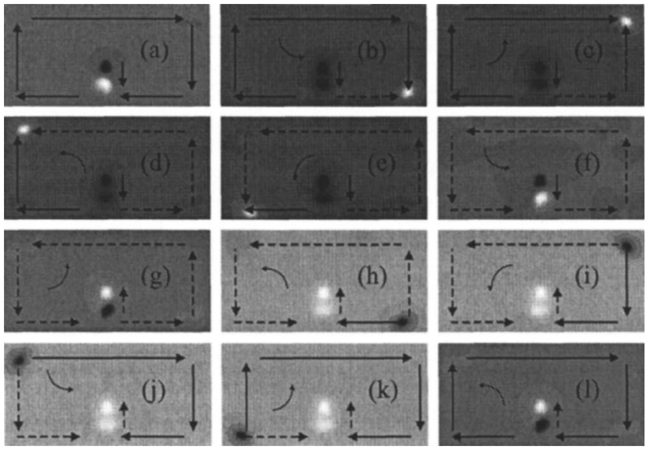

FIG. 4. Simulated magnetization and stray field from the ring structure after the application of magnetic fields in different directions, indicated by the arrows inside the structure outline. Gray scale is used, the white indicates the positive stray field, while the black shows the negative stray field. Successive quasi-static magnetic fields are assumed to simulate a counter-clockwise rotating field. Arrows in the profile of the structure indicate the magnetization orientation. Reversed magnetization due to domain-wall propagation are additionally indicated by changing from a solid to a dashed line. The black and white spots indicate the stray field from the structure that MFM tip is sensitive to.

area in the initialized magnetization state shown in Fig. 1(c). The magnetization in the stub region is parallel to the wire, where there is a head-to-head domain wall close to the right side of the junction region. In order to move this domain wall out of the junction area, a magnetic field is required in the direction of the output wire, as indicated in Fig. 3(a). After applying this field, the domain wall is moved to the next corner in the ring [Fig. 3(b)]. This corresponds to the white spot observed in Fig. 2(b). The magnetization in the cusp is now symmetrical. In the junction region, magnetizations from the two ring wires oppose each other, as in a tail-to-tail domain wall, leading to an overall negative magnetic charge. This is why MFM generates two black spots above a junction in this magnetization state. The head-to-head domain wall at the ring corner can propagate through the wire ring under relatively low magnetic fields. After a complete cycle of magnetic field, the head-to-head domain wall moves back to the junction area but now from the right hand wire [Fig. 3(c)]. Once a field is applied in the direction of the stub length, the (tail-to-tail) domain wall lies on the left-hand side of the junction again and the stub magnetization is reversed [Fig. 3(d)]. The situation is now identical to Fig. 3(a) except that all magnetization directions have been reversed. This situation was obtained after 1.5 periods of the in-plane rotation magnetic field, as observed previously.[4,5] To continue domain-wall propagation requires application of a magnetic field in a direction indicated by arrow in Fig. 3(d).

To make a direct comparison, we have calculated the out-of-plane stray field map at remanence from simulations at different stages of domain-wall propagation around the structure (Fig. 4). There is excellent agreement between the simulated and experimentally observed stray fields from both the propagating domain wall and the cusp region. The micromagnetic simulations also confirm the experimental observation that the required field is larger than 50 Oe, in order to reverse the magnetization of the stub region. Furthermore, simulations indicate that for a magnetic field of greater than 200 Oe the entire ring structure becomes magnetized in the direction of the field. Upon removal of this field, a head-to-head and a tail-to-tail domain wall are introduced to the ring. This is highly undesirable for information processing applications and applied fields need to be chosen appropriately to avoid this, as demonstrated previously.[5] However, the simulations show that domain walls propagate along the straight wire sections at fields as low as 5 Oe, although the domain-wall velocity is reduced.

In conclusion, field-induced domain-wall propagation in a ferromagnetic nanowire structure of a ring integrated with a logical NOT junction has been studied by MFM. These measurements can distinguish between head-to-head and tail-to-tail domain walls as well as determine the magnetization state of the NOT junction region. The domain-wall propagation and depinning associated with operation of the device is observed in detail under appropriate field conditions. Furthermore, the inverting nature of the wire junction is confirmed by observing the domain-wall switch between tail-to-tail and head-to-head types as they propagate through the NOT-gate element. MFM observations and micromagnetic simulations confirm that the minimum field conditions for propagating a domain wall continuously around the structure are due to domain-wall depinning in the NOT junction.

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