Shift registers based on magnetic domain wall ratchets with perpendicularly anisotrpoy

Citation for published version (APA):
Franken, J. H., Swagten, H. J. M., & Koopmans, B. (2012). Shift registers based on magnetic domain wall ratchets with perpendicularly anisotrpoy. *Nature Nanotechnology*, *7*(8), 499-503. https://doi.org/10.1038/NNANO.2012.111

DOI:
10.1038/NNANO.2012.111

Document status and date:
Published: 01/01/2012

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 22. Aug. 2022

nature
nanotechnology

LETTERS

| DOI: 10.1038/NNANO.2012.111

Shift registers based on magnetic domain wall ratchets with perpendicular anisotropy

J. H. Franken*, H. J. M. Swagten and B. Koopmans

The movement of magnetic domain walls can be used to build a device known as a shift register, which has applications in memory[1] and logic circuits[2,3]. However, the application of magnetic domain wall shift registers has been hindered by geometrical restrictions, by randomness in domain wall displacement and by the need for high current densities or rotating magnetic fields. Here, we propose a new approach in which the energy landscape experienced by the domain walls is engineered to favour a unidirectional ratchet-like propagation. The domain walls are defined between domains with an out-of-plane (perpendicular) magnetization, which allows us to route domain walls along arbitrary in-plane paths using a time-varying applied magnetic field with fixed orientation. In addition, this ratchet-like motion causes the domain walls to lock to discrete positions along these paths, which is useful for digital devices. As a proof-of-principle experiment we demonstrate the continuous propagation of two domain walls along a closed-loop path in a platinum/cobalt/platinum strip.

Although later abandoned, magnetic shift registers were already under consideration in the early 1970s (refs 4,5). Since then, exciting developments in spintronics have led to nanometre-sized versions that are at present subject to active investigation. One prominent example is the magnetic racetrack memory[1], in which the magnetic domain walls are driven by current instead of magnetic fields. A key motivation for using current lies in the fact that two neighbouring domain walls will move towards one another when a field is applied, erasing the bit stored between them as they annihilate. However, sending large currents through tiny wires raises practical issues, primarily related to heating[6]. Currents are not required in the 'domain wall logic' scheme[2,3], which uses a carefully shaped permalloy track capable of storing, moving and performing logic operations on magnetic domain walls, using in-plane rotating magnetic fields as a clock. However, this scheme imposes very strong geometrical constraints, and rotating in-plane fields are particularly hard to integrate into a chip.

Our approach makes use of materials with perpendicular magnetic anisotropy (PMA), which exhibit narrow domain walls (~10 nm), allowing for a higher storage density compared with in-plane magnetized materials. The key is to create a domain wall ratchet. In other words, the domain wall should move easily in one direction, while motion is blocked in the other[7–13]. Some means by which to achieve this have been proposed for in-plane magnetized systems, including using the stray field of nearby magnetic elements[12,13], non-uniform transverse magnetic fields[14] or geometrical variations[7–9]. However, these effects are rather weak compared with the strong anisotropy field in PMA materials. To carefully control domain wall motion in PMA ratchets, we therefore chose to engineer the domain wall energy landscape directly by modulating the magnetic anisotropy. Ion irradiation using a focused ion beam (FIB)[15,16] provides an elegant way to tune this parameter on a nanometre scale[17–19]. Figure 1 presents the ion irradiation pattern on a magnetic nanostrip. Higher irradiation doses lead to lower PMA and therefore a lower domain wall energy, giving the desired sawtooth-like potential landscape for the domain walls.

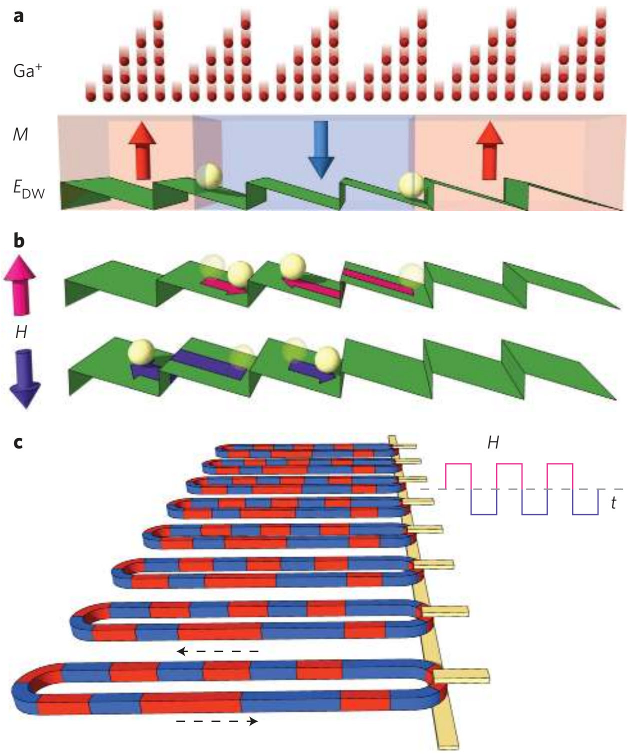

Figure 1 | Domain wall ratchet shift register. a, Magnetic nanostrip with perpendicular magnetic anisotropy exhibits magnetic domains with a magnetization (M) pointing up (red) or down (blue). The energy landscape E_{DW} (green) experienced by the domain walls (yellow beads) can be engineered by irradiating the strip with gallium ions (Ga^+) of varying intensity. **b**, Force exerted on the domain walls by a positive (pink) applied magnetic field (H) pushes the domain walls together, while a negative (violet) field pushes them apart. By applying a positive and then a negative pulse of appropriate length, both domain walls move to the left. **c**, Possible implementation in a memory device. Loops are used to conserve the data indefinitely. A global magnetic field can be used for all loops, or each loop can be addressed individually. Data input/output can be integrated, for example by placing a magnetic tunnel junction at a single position along each track, where the track acts as a free layer. Alternatively, writing schemes involving the magnetic field can be devised, for example by engineering a position where the domain wall nucleation field is reduced, such that a brief increase in the field amplitude can write a bit at this position.

Department of Applied Physics, Center for NanoMaterials, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands.
*e-mail: j.h.franken@tue.nl

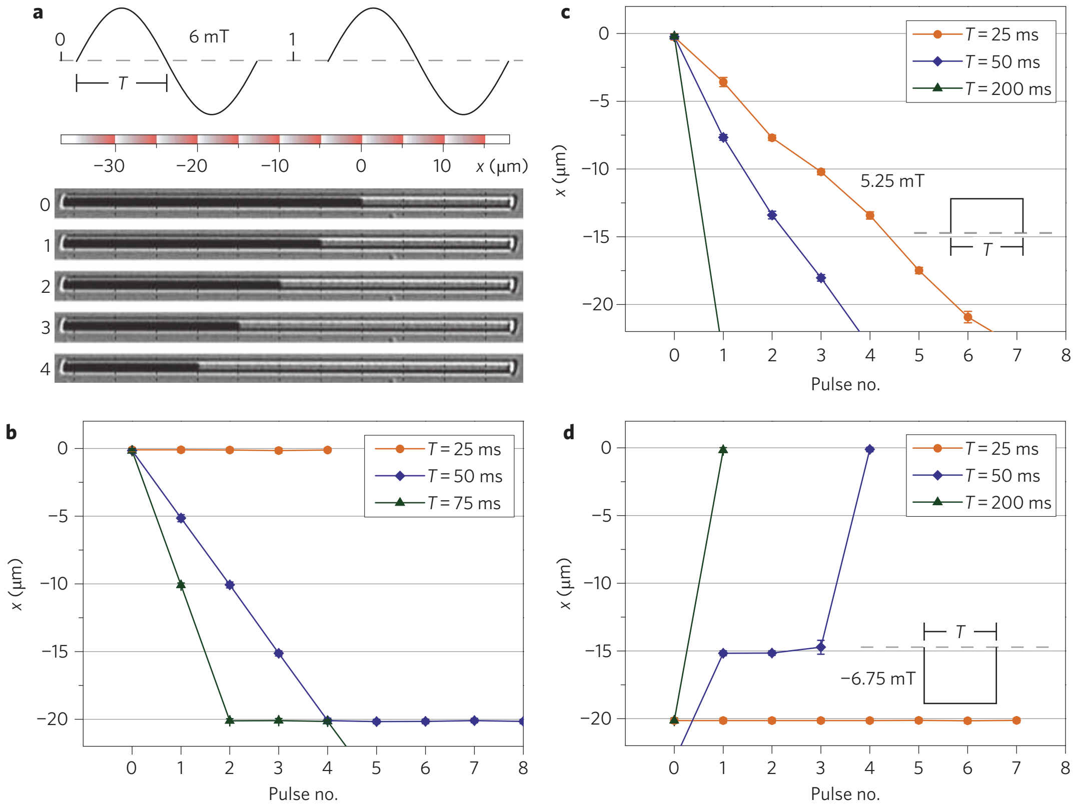

Figure 2 | Demonstration of the ratchet effect in a platinum/cobalt/platinum strip. a, A 1-µm-wide strip is patterned with a linearly increasing gallium irradiation dose (red indicates maximum) in 5 µm periods. Kerr microscopy snapshots are taken between 6 mT sinusoidal field pulses with a half-period of $T = 50$ ms. **b**, Domain wall position as a function of pulse number under various pulse durations T. **c**,**d**, Different effect of positive (**c**) and negative (**d**) field pulses. In **c** it is shown that the domain wall pins at a random position after each positive field pulse. A much higher negative field was necessary in **d** to achieve any domain wall motion, and the domain wall position clearly locks to the steep energy barriers.

When a positive field is applied, a force is exerted on the domain walls, pushing them towards one another to minimize the Zeeman energy, $-\mu_0\mathbf{M}\cdot\mathbf{H}$. However, the sudden step in anisotropy provides an energy barrier, prohibiting the left domain wall from moving to the right. By appropriate timing of the field pulse, the right domain wall will move to a new position within the next ratchet period. A subsequent opposite field pulse will then move this domain wall back to its new base position, and the left domain wall will propagate. As long as the distance between two domain walls is at least two periods, an a.c. field can be used to propagate both domain walls in the same direction, while providing discrete positions where the domain walls will stop, which is crucial in a digital device. To prevent data loss at the ends of the strip, one simply makes a loop in which data can propagate indefinitely.

This scheme has some unique and powerful advantages when implemented in a memory device. Because the magnetization is perpendicular to the plane, we have complete freedom to route our domain walls within the film plane, thereby allowing the creation of loops to propagate data indefinitely. In contrast to in-plane rotating fields[2], a perpendicular magnetic field is easy to produce, for example from the Oersted field of current lines coplanar to the magnetic structure. A possible implementation in a two-dimensional memory architecture, including read and write access, is presented in Fig. 1b. In the remainder of this Letter we focus on the principal feature of this device, demonstrating the unidirectional propagation of multiple domain walls.

A first test of the working principle of our device is presented in Fig. 2a. After preparing a domain wall in a patterned platinum/cobalt/platinum strip, sinusoidal pulses with amplitude 6 mT and period $T = 50$ ms were applied, and the magnetic state was imaged after each pulse. The domain wall, initially at $x = 0$, moves a distance -5 µm with each pulse, corresponding to the period and direction of the ratchet landscape. This illustrates that we have successfully created a ratchet: the time-average magnetic field is zero, but the domain wall still moves to the right and locks to discrete energy minima after each pulse. Figure 2b shows the domain wall position as a function of pulse number under various pulse durations T. Optimal motion over four periods is observed for $T = 50$ ms. After four periods the domain wall is blocked by a random pinning site and does not easily move beyond -20 µm.

To elucidate the different effects of positive and negative fields on domain wall propagation, measurements with unipolar field pulses were also performed. In Fig. 2c, low field pulses of 5.25 mT were applied in the easy propagation direction. Rather than reverting to the engineered energy minima, the domain wall stays at arbitrary positions after each pulse due to the random pinning potential of the material, which is superposed on the engineered potential. In Fig. 2d, a significantly higher opposite field of -6.75 mT was applied to move domain walls against the ratchet direction. As expected, the domain wall now tends to stop at discrete pinning positions that block its motion.

We then applied the demonstrated ratchet functionality in a shift register, where it is vital to propagate multiple domain walls without annihilation. We therefore created ring structures consisting of eight ratchet periods and studied the simultaneous motion of two domain walls around the ring (Fig. 3). Instead of defining the rings lithographically, we used a unique technique that we call magnetic etching (see Methods). After nucleating a pair of domain walls, field pulses of alternating polarity were applied, and the configuration imaged after each pulse is shown in Fig. 3b. It can be seen that, each time,

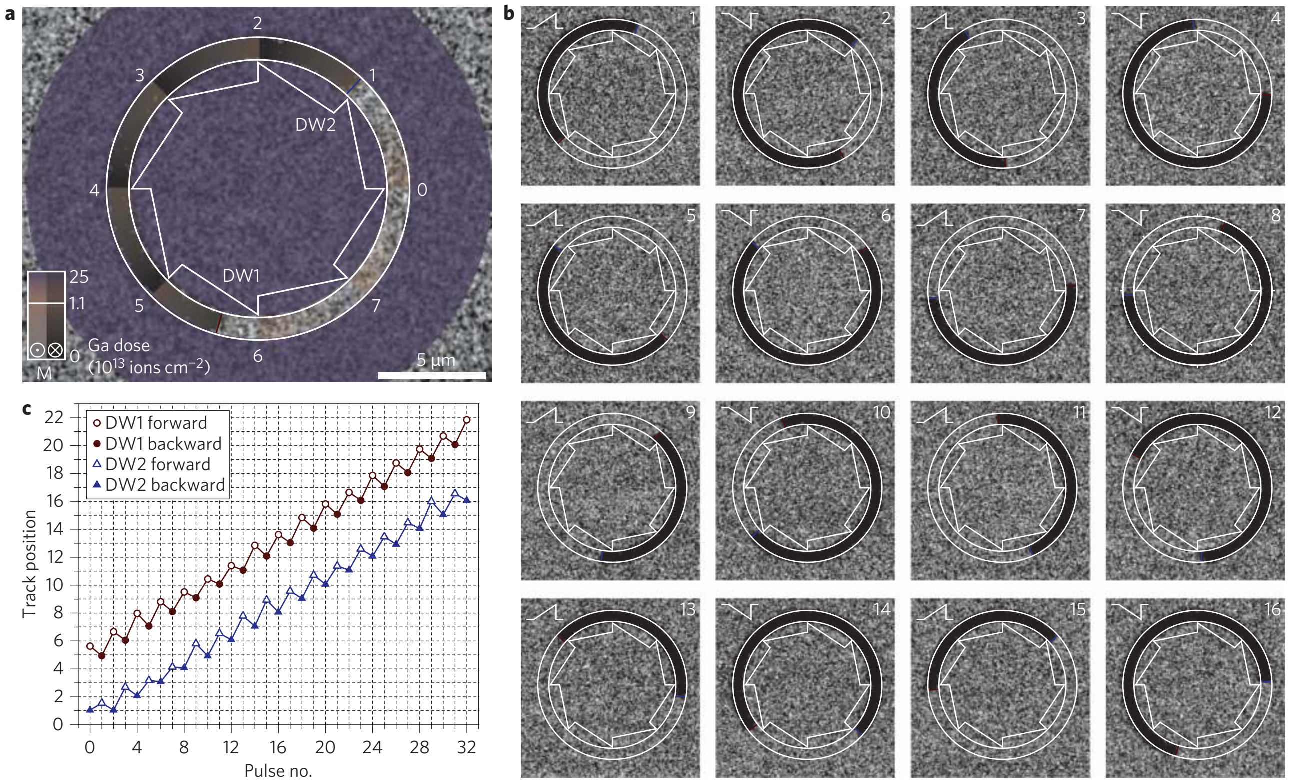

Figure 3 | Proof-of-principle operation of two domain walls in a circular loop. a, Kerr microscopy image of the initial magnetic state of a ring with two domain walls (blue and red lines), with the colour overlay indicating the FIB dosage. A magnetic loop is created by high-dose irradiation of the surrounding areas (purple). Eight ratchet potentials are defined within the loop at the same time, by subtle dose variations. The background of the positively saturated remnant state was subtracted from the image to improve contrast, so that black means negative magnetization and grey means positive magnetization (on the ring) or zero magnetization (outside of the ring). The dosage is indicated with a separate colour bar for each contrast level. **b**, Magnetic state and fitted domain wall positions after consecutive positive and negative ramped field pulses (15.8 mT, 73 ms). **c**, Domain wall position as a function of pulse number showing near perfect discrete propagation of both domain walls over two full loops.

one of the domain walls moves anticlockwise to a position within the next segment, whereas the other domain wall locks back to the base position of the current segment. The detected positions of both domain walls are plotted as a function of pulse number in Fig. 3c. The domain walls complete two full loops around the track without annihilating, demonstrating the feasibility of our approach.

The performance statistics of one ratchet ring are studied as a function of the pulse parameters in Fig. 4. By separating the statistics of forward and backward motion, we can identify the forward motion as the bottleneck in ratchet performance; the success of backward motion is close to unity in the entire parameter range (Fig. 4b). Averaged over all events, an optimal forward success ratio of ~80% is observed in Fig. 4a. As expected, the optimal length of the field pulse decreases as the field amplitude is increased. The maximum average success is limited to 80% due to random growth variations in the sample, leading to slightly different optimal pulse parameters for each of the eight individual ratchets. There are also some ratchets that have lower success over the entire parameter range, for example because of a relatively hard pinning site that hampers forward motion. In Fig. 4d,e, it is shown that both the forward (Fig. 4d) and backward (Fig. 4e) success rates of a selected single ratchet segment (indicated in the insets) can be brought close to unity. Therefore, limited success is not a principal problem but is rather a matter of engineering the material so that all ratchets show a larger overlap in their operating range.

The combined forward/backward success plotted in Fig. 4c closely resembles the forward statistics in Fig. 4a, as expected given the high success of backward motion. The optimal period as a function of amplitude fits well to a power law (see Methods). Figure 4f shows the average distance d (expressed in number of ratchet periods) traversed by a domain wall during a forward pulse, with a darker colour indicating a larger distance. It is seen that if the field pulse is too long or too high, the domain wall can move on average by more than two periods, which means a ratchet period is skipped. We find that over the entire field range, success is optimal if the period is tuned to move the domain wall (on average) by $d \approx 1.5$, which is intuitive as this average domain wall displacement coincides with the centre of the success range ($1 < d < 2$).

In conclusion, we have experimentally demonstrated a field-driven domain wall shift register by engineering a ratchet potential in a platinum/cobalt/platinum nanotrack. The demonstration of unidirectional domain wall motion changes the current paradigm, which excludes simple magnetic fields as a driving force. Furthermore, in most of the reported work on (current-driven) domain wall motion, the domain wall positions are random, but in our scheme domain walls efficiently lock to discrete positions. However, the data rate of a future memory device is limited by the domain wall speed divided by the ratchet period. In our proof-of-principle experiment, domain wall speeds were limited to ~100 μm s^{-1} by the slow electromagnet we used, but fast motion of >100 m s^{-1} is feasible, simply by using higher, shorter pulses to change from the creep regime to the flow regime of domain wall motion[20]. To confirm that the principle still holds in this regime, a micromagnetic simulation was performed on a nanowire with a ratchet period of 100 nm and with 8 ns, 50 mT field pulses,

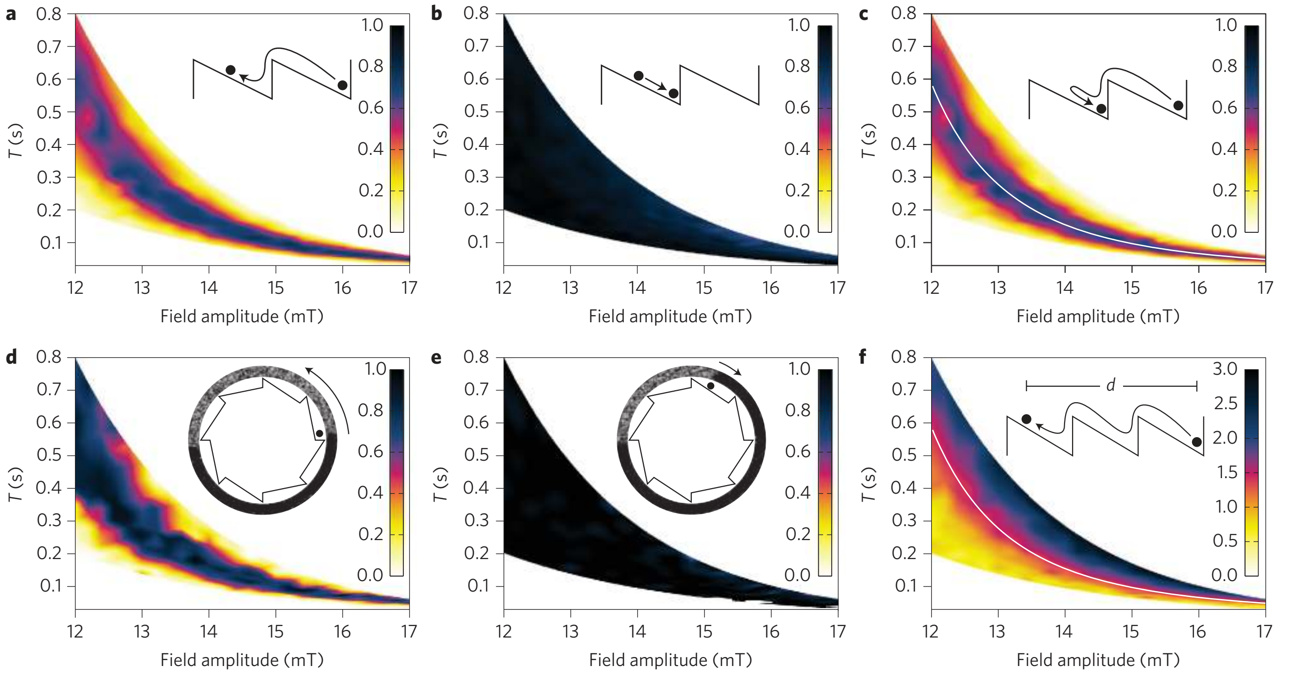

Figure 4 | Statistics of ratchet operation as a function of pulse duration and amplitude. a, Success ratio of forward domain wall displacement to a position within the next ratchet period, averaged over all measured events. **b**, Success of backward domain wall motion; in nearly all cases the domain wall locks to the base of the period it was previously in. **c**, Composite success of both forward and backward motion after a pair of positive and negative pulses. The statistics are clearly dominated by the success of forward motion. The white line is a fit through the optimal points. **d**,**e**, Similar to **a** and **b**, but only showing the statistics of motion of one selected ratchet segment on the ring (defined in the insets). **f**, Average distance travelled by a domain wall in response to a forward pulse. In **f**, the colour code represents the number of ratchet periods *d* over which the domain wall has moved. The white line representing optimal success coincides with $d \approx 1.5$ periods over the entire parameter range.

yielding stable ratchet operation (Supplementary Movie S1). Like any domain wall shift register, the bit size is ultimately limited to a few times the domain wall width to ensure a stable configuration (therefore ~50 nm in platinum/cobalt/platinum).

Field-driven memory has many advantages, such as a potentially low power dissipation per operation[3] and much longer device lifetime, which is limited by electromigration when charge currents are used. However, the discrete nature of our device is also beneficial when any other driving force is used, and could also be applied in current-driven shift registers using spin transfer torque or the recently discovered spin–orbit torque[21,22]. Using a.c. currents, the induced torques could lead to ratchet propagation of domain walls in a fixed direction between two contacts. Here, it would be particularly powerful if one could invert the ratchet direction during operation, so the bits could simply be shifted back and forth past a central reading head. This requires a programmable domain wall energy landscape, which could be realized using the recently demonstrated electric field control of domain wall motion[23]. Another interesting next step would be to integrate logic functionality similar to the in-plane domain wall logic scheme[3], to create a fully magnetic memory and logic device from PMA materials. Furthermore, rather than finding use in computer-related applications, the stray fields of propagating domain walls could also be used as a particle conveyor belt in chemical/biosensors[24,25].

Methods

The 1-μm-wide platinum (4 nm)/cobalt (0.5 nm)/platinum (2 nm) strips of Fig. 2 were produced by electron-beam lithography (EBL), sputtering and lift-off, followed by a gallium ion FIB irradiation step. The perpendicular anisotropy of this material as a function of gallium dose has been measured in ref. 19. The gallium dose was increased from 0.05×10^{13} ions cm^{-2} to 0.5×10^{13} ions cm^{-2} over a distance of 5 μm. This optimal gallium dose range is a balance between achieving an anisotropy step that is sufficiently high to achieve domain wall pinning and maintaining a high enough nucleation field to prevent spontaneous nucleation of domains by propagation pulses. To initialize a domain wall, a short high negative field pulse was applied to a positively saturated wire, reproducibly creating the configuration seen in the first Kerr microscope image.

For the ratchet rings, we started from an unpatterned tantalum (15 nm)/platinum (4 nm)/cobalt (0.5 nm)/platinum (4 nm) film, with the thick tantalum seed layer serving to improve the growth quality and significantly increasing the range of gallium doses that could be applied before the perpendicular magnetization was destroyed. We used a technique that we call magnetic etching, which allowed us to fabricate devices simply from a homogeneous film in a single gallium irradiation run. A magnetic ring was 'etched' by irradiating the surroundings (dark purple region in Fig. 3a) with a relatively high gallium dose of 25×10^{13} ions cm^{-2}, enough to destroy the magnetic anisotropy, but not enough to physically remove a significant amount of material. Within the ring, a much lower dose was used, which linearly increased from 0.02×10^{13} to 1.1×10^{13} ions cm^{-2} in each of the eight segments in the clockwise direction, favouring domain wall propagation in the anticlockwise direction. This pattern was designed using line segments of constant dose pointing radially outward, separated by 40 nm. In principle, this yielded a slightly higher dose in the inner boundary of the ring compared to the outer boundary, as the distance between the dose lines was smaller closer to the centre. A preparatory pulse was then applied to create two domain walls at random positions. A sequence of 32 field pulses (as used in Fig. 3) was repeated for 286 period/amplitude combinations, and each combination was repeated 10 times. This yielded nearly 100,000 images, from which the domain wall positions were detected using a MATLAB script. From this list of domain wall positions we were able to track the distance moved by the domain walls after each pulse and determine whether the domain wall behaviour was successful or not (Fig. 4). Forward success is defined as motion to a position within the next ratchet period, and backward success by a domain wall remaining in position within the current ratchet period following a backward directed field pulse. Composite success indicates that a domain wall consecutively experiences successful forward and backward motion. For optimal success in ratchet rings, longer pulses or higher field strengths are required than were used in the experiment on straight strips shown in Fig. 2. This is a consequence of the different material used (the tantalum seed layer increases the anisotropy, which decreases the domain wall speed in the creep regime), the ramped pulse shape (where the maximum field strength is applied only very briefly) and possibly the different lithography method (EBL versus FIB magnetic etching).

The fit (white line in Fig. 4c) through the optimal period as a function of field amplitude H is of the form $T_{\text{opt}} \propto e^{CH^{-\mu}}$, where $\mu = 2.2$ and C is a constant. It is hard to ascribe a physical mechanism to exponent μ. For domain wall motion under a constant field through a uniform medium, $\mu = 0.25$ is expected in the low-field creep regime[20,26]. However, our field pulse is ramped, and the exact shape of the domain wall potential in the ratchet is a complicating factor, because a linear irradiation gradient does not necessarily lead to a linear potential landscape. For each of the individual ratchets, we find a different μ ranging between 1.5 and 2.8, so this parameter is strongly related to the local material structure.

Received 7 March 2012; accepted 1 June 2012;

References

1. Parkin, S. S. P., Hayashi, M. & Thomas, L. Magnetic domain-wall racetrack memory. *Science* **320,** 190–194 (2008).
2. Allwood, D. A. *et al.* Submicrometer ferromagnetic NOT gate and shift register. *Science* **296,** 2003–2006 (2002).
3. Allwood, D. A. *et al.* Magnetic domain-wall logic. *Science* **309,** 1688–1692 (2005).
4. Hayashi, N., Romankiw, L. & Krongelb, S. An analysis of a clear-view angelfish bubble-domain shift register. *IEEE Trans. Magn.* **8,** 16–22 (1972).
5. Bobeck, A., Bonyhard, P. & Geusic, J. Magnetic bubbles: an emerging new memory technology. *Proc. IEEE* **63,** 1176–1195 (1975).
6. You, C-Y., Sung, I. M. & Joe, B-K. Analytic expression for the temperature of the current-heated nanowire for the current-induced domain wall motion. *Appl. Phys. Lett.* **89,** 222513 (2006).
7. Allwood, D. A., Xiong, G. & Cowburn, R. P. Domain wall diodes in ferromagnetic planar nanowires. *Appl. Phys. Lett.* **85,** 2848–2850 (2004).
8. Himeno, A., Kasai, S. & Ono, T. Depinning fields of a magnetic domain wall from asymmetric notches. *J. Appl. Phys.* **99,** 08G304 (2006).
9. Bryan, M. T., Schrefl, T. & Allwood, D. A. Symmetric and asymmetric domain wall diodes in magnetic nanowires. *Appl. Phys. Lett.* **91,** 142502 (2007).
10. Pérez-Junquera, A. *et al.* Crossed-ratchet effects for magnetic domain wall motion. *Phys. Rev. Lett.* **100,** 037203 (2008).
11. Yamaguchi, A., Kishimoto, T. & Miyajima, H. Asymmetric domain wall propagation in a giant magnetoresistance-type wire with oscillating interlayer exchange coupling. *Appl. Phys. Express* **3,** 093004 (2010).
12. Piao, H-G., Choi, H-C., Shim, J-H., Kim, D-H. & You, C-Y. Ratchet effect of the domain wall by asymmetric magnetostatic potentials. *Appl. Phys. Lett.* **99,** 192512 (2011).
13. O'Brien, L. *et al.* Tunable remote pinning of domain walls in magnetic nanowires. *Phys. Rev. Lett.* **106,** 087204 (2011).
14. You, C-Y. Another method for domain wall movement by a nonuniform transverse magnetic field. *Appl. Phys. Lett.* **92,** 152507 (2008).
15. Chappert, C. *et al.* Planar patterned magnetic media obtained by ion irradiation. *Science* **280,** 1919–1922 (1998).
16. Hyndman, R. *et al.* Modification of Co/Pt multilayers by gallium irradiation. Part 1: The effect on structural and magnetic properties. *J. Appl. Phys.* **90,** 3843–3849 (2001).
17. Lavrijsen, R., Franken, J. H., Kohlhepp, J. T., Swagten, H. J. M. & Koopmans, B. Controlled domain-wall injection in perpendicularly magnetized strips. *Appl. Phys. Lett.* **96,** 222502 (2010).
18. Franken, J. H. *et al.* Precise control of domain wall injection and pinning using helium and gallium focused ion beams. *J. Appl. Phys.* **109,** 07D504 (2011).
19. Franken, J. H., Hoeijmakers, M., Lavrijsen, R. & Swagten, H. J. M. Domain-wall pinning by local control of anisotropy in Pt/Co/Pt strips. *J. Phys. Condens. Matter* **24,** 024216 (2012).
20. Lemerle, S. *et al.* Domain wall creep in an Ising ultrathin magnetic film. *Phys. Rev. Lett.* **80,** 849 (1998).
21. Miron, I. M. *et al.* Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. *Nature* **476,** 189–194 (2011).
22. Liu, L. *et al.* Spin-torque switching with the giant spin Hall effect of tantalum. *Science* **336,** 555–558 (2012).
23. Schellekens, A. J., van den Brink, A., Franken, J. H., Swagten, H. J. M. & Koopmans, B. Electric-field control of domain wall motion in perpendicularly magnetized materials. *Nature Commun.* **3,** 847 (2012).
24. Ehresmann, A. *et al.* Asymmetric magnetization reversal of stripe-patterned exchange bias layer systems for controlled magnetic particle transport. *Adv. Mater.* **23,** 5568–5573 (2011).
25. Rapoport, E. & Beach, G. S. D. Dynamics of superparamagnetic microbead transport along magnetic nanotracks by magnetic domain walls. *Appl. Phys. Lett.* **100,** 082401 (2012).
26. Metaxas, P. *et al.* Creep and flow regimes of magnetic domain-wall motion in ultrathin Pt/Co/Pt films with perpendicular anisotropy. *Phys. Rev. Lett.* **99,** 217208 (2007).

Acknowledgements

This work is part of the research programme of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO).

Author contributions

J.H.F. devised the concept, designed and performed the experiments, performed the data analysis and prepared the manuscript. H.J.M.S. and B.K. accommodated the experiments, assisted in the analysis and commented on the final manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper at www.nature.com/naturenanotechnology. Reprints and permission information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.H.F.