Control of domain wall pinning by switchable nanomagnet state

AIP | Journal of Applied Physics

Control of domain wall pinning by switchable nanomagnet state

R. A. van Mourik, C. T. Rettner, B. Koopmans, and S. S. P. Parkin

Citation: Journal of Applied Physics **115**, 17D503 (2014); doi: 10.1063/1.4862216
View online: http://dx.doi.org/10.1063/1.4862216
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/115/17?ver=pdfcov
Published by the AIP Publishing

Control of domain wall pinning by switchable nanomagnet state

R. A. van Mourik,[1,2,a)] C. T. Rettner,[1] B. Koopmans,[2] and S. S. P. Parkin[1]
[1]IBM Almaden Research Center, San Jose, CA 95120, USA
[2]Eindhoven University of Technology, Eindhoven, the Netherlands

(Presented 5 November 2013; received 23 September 2013; accepted 18 October 2013; published online 21 January 2014)

We report on a novel approach to establish switchable pinning of magnetic domain walls in a nanowire with perpendicular magnetic anisotropy by a single in-plane magnetized single-domain nanomagnet positioned on top of the wire. Devices were prepared by depositing a permalloy nanomagnet on top of a nanowire formed from a Co/Ni multilayer with their long axes parallel, separated by a nonmagnetic layer. We show by electrical measurements that the domain wall pinning strength depends critically on the state of the bistable nanomagnet and can differ by more than 10 mT. We also performed micromagnetic calculations that show that the difference in pinning strength is caused by the interaction of the forced Néel wall with the nanomagnet's magnetostatic field. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4862216]

I. INTRODUCTION

Magnetic domain walls (DWs) are versatile nanoscale objects that have many technological applications. Specifically, the dynamics of DWs such as their propagation through a magnetic medium, whether by field or current, promises to be highly important in logic[1] and memory devices.[2] Precise control of positioning of the DWs is necessary for operation of such technologies, and one way to do this is to create pinning sites. In the case of a magnetic nanowire, an easy and conventional way to create a pinning site is by cutting a geometrical notch into the long edge of the wire. Other methods include irradiating areas of the nanowire[3] or having nanomagnets to the side of the nanowire whose fringing fields affect the movement of the DW.[4,5] It has also been shown that two nanomagnets on either side of an in-plane magnetized nanowire will trap a DW, where the pinning strength depends on the aggregate state of the nanomagnets.[6]

In this article, we present switchable pinning of a DW in a nanowire with perpendicular magnetic anisotropy (PMA) by a single nanomagnet, where the magnetic state of the nanomagnet determines the pinning strength at the site. The nanowire is a Co/Ni multilayer, which exhibits PMA. A thin rectangularly shaped permalloy nanomagnet is deposited above the nanowire, separated by a thin nonmagnetic layer, with the long axis of the nanomagnet oriented parallel to the nanowire long axis. The nanomagnet is sufficiently small that it is uniformly magnetized, and, because of the nanomagnet's shape, the magnetization is pointed in one of two directions parallel to its long edge, i.e., the nanomagnet can be set in one of two states. The fringing field from the nanomagnet forms a pinning site for the DW separating out-of-the-plane and into-the-plane domains along the nanowire. We show using electrical measurements that the out-of-plane magnetic field required to depin the DW from the pinning site depends on the magnetic state of the nanomagnet. This paper presents experimental results that confirm the expected DW pinning phenomenon, as well as micromagnetic calculations that establish that the fine structure of the DW is responsible for the dependence of pinning strength on the nanomagnet state.

II. EXPERIMENTAL SETUP

Devices, as depicted in Figure 1, were fabricated as follows. First, a film exhibiting PMA was deposited on a Si wafer covered with a thick SiO_2 layer, consisting of a TiAl underlayer, 3 ÅCo, and five repeats of 1.5 ÅCo/7 ÅNi bilayers. The film was patterned into nanowires 110 nm wide and several μm long by electron beam lithography and successive ion milling. A permalloy nanomagnet measuring 60×90 nm^2 and 10 nm thick is deposited on top of each nanowire, separated by a 5 nm TaN layer, by electron beam evaporation through holes patterned by electron beam lithography using PMMA resist, so that its long axis is parallel to the wire axis. A TaAu contact is placed at the downstream end of the wire, and at the upstream end a TaAu bar crosses the nanowire, serving a dual purpose as a contact for the anisotropic magnetoresistance (AMR) measurement and a DW injection line. There is also a Ru bar crossing the wire (Hall bar) downstream of the nanomagnet, which exploits the anomalous Hall effect to reveal the local wire magnetization state.

The nanomagnets' size dictates that their magnetization is single-domain, and their shape dictates that the easy axis of magnetization is along their long axis. This implies that the nanomagnet's magnetization can be in two stable states: pointing downstream along the nanowire (right) or upstream (left). The nanomagnets in all of the devices are set in a particular state (right or left) by applying a global field of 0.1 T along the nanomagnet axis in the desired direction.

A single pinning strength measurement in any particular device is composed of several steps. First, a pulse is applied through the DW injection line (step 1). The pulse locally switches the magnetization in the PMA nanowire in the region where the Oersted field opposes the wire

a)Electronic mail:rvmourik@us.ibm.com.

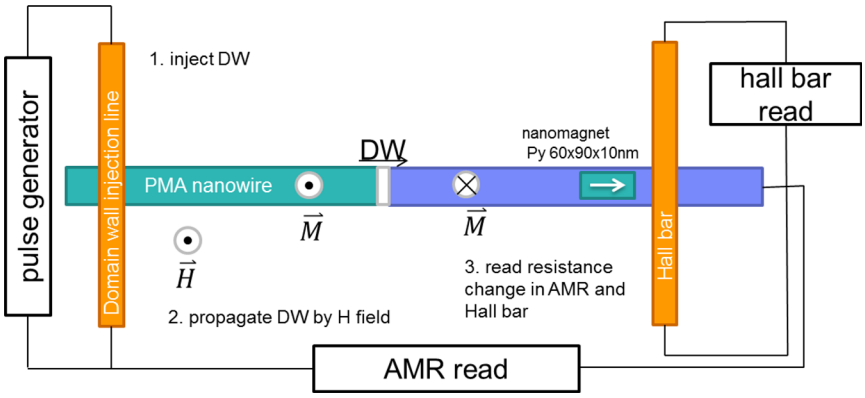

FIG. 1. Experimental setup. A nanomagnet is deposited on top of a nanowire exhibiting perpendicular magnetic anisotropy, separated by a thin layer. A DW is injected into the nanowire (step 1) and moved towards the nanomagnet (step 2), where it is pinned. The field is increased until the DW is depinned and exits the wire, which is measured as a change in AMR and Hall bar voltage (step 3).

magnetization, creating a reversed domain and two DWs. One DW exits the wire at the upstream end. The other DW, separating an out-of-the-plane (up) from an into-the-plane region (down), will have one of two polarities, up-down (ud) or down-up (du) (upstream-downstream side), depending on the inital magnetization of the nanowire. Successful nucleation of a DW is revealed by a small increase in the nanowire resistance due to AMR. Next, an out-of-plane (oop) global field is applied and gradually increased (step 2), during which the DW is depinned from its starting location and becomes pinned at the nanomagnet site. Further increase of the field depins the DW from the nanomagnet site, after which the DW exits the wire. The latter is registered by the disappearance of the increase in the AMR signal as well as a change in the Hall bar resistance just downstream from the nanomagnet (step 3) because the local nanowire magnetization is changed by the passing DW. The measurement is repeated for the other nanomagnet state and the other DW polarity. The latter can be done readily, since performing the measurement reverses the entire nanowire magnetization. Symmetry predicts that for any of the measurements above, the depinning fields for the configurations $(\mathrm{ud}, \leftarrow)$ and $(\mathrm{du}, \rightarrow)$ should be equal but opposite and *idem dito* for $(\mathrm{du}, \leftarrow)$ and $(\mathrm{ud}, \rightarrow)$.

III. RESULTS AND DISCUSSION

The experimental procedure has been applied to a large number of devices; a typical result is shown in Figure 2 for both right- and left-magnetized states of the nanomagnet. After a DW is injected, the nanowire resistance due to AMR rises by $\sim 0.2\,\Omega$. At ~ 5 mT, the DW moves to the pinning site underneath the nanomagnet. Evidence hereof is a decrease of $\sim 0.05\,\Omega$ in the AMR signal attributable to a change in the internal structure of the DW by the nanomagnet's fringing field. At ~ 10 mT (right-magnetized) and ~ 21 mT (left-magnetized), the DW is depinned and passes underneath the Hall bar, reversing the local magnetization of the nanowire, which is registered by a change in resistance measured in the Hall bar by $\sim 0.07\,\Omega$. Immediately thereafter, the DW exits the wire, which returns the resistance due to AMR to its pre-injection level. The figure shows clearly that the difference in depinning field for the two nanomagnet states is more than 10 mT.

The measurement is repeated many times and averaged, which shows that for this device, the right-magnetized and left-magnetized depinning fields are 10.2 mT and 20.8 mT, respectively. The measurement is also performed for a DW of the opposite polarity, where the depinning fields for this device are found to be -24.6 mT and -9.2 mT, respectively, in reasonable agreement with the predicted aforementioned symmetry. The discrepancy may arise from incomplete magnetization reversal of the nanomagnet due to, for example, stress-induced anisotropies along its edges. Depinning field differences are observed in (almost) all of the properly functioning devices.

The entire life cycle of the DW is observed. Its creation triggers a rise in AMR signal. Its depinning from its injection location can be seen as in the AMR signal as well, as a decrease of $\sim 0.05\,\Omega$. Furthermore, we have also carried out the experiments on devices where the Hall bar is upstream of the nanomagnet. This means that the Hall bar signal changes when the DW moves towards the pinning site, and the AMR signal changes when it leaves (not shown). The magnitude of the DW movement field varies between 3 and 10 mT but is significantly less than the depinning field and, as expected, similar but opposite for up-down and down-up DWs.

The difference in propagation fields for the two magnetization states of the nanomagnet becomes apparent when the energy landscape that the DW encounters near the

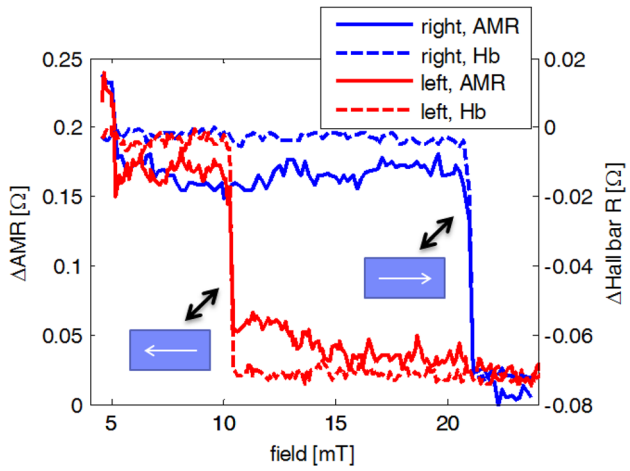

FIG. 2. Change in nanowire resistance due to AMR and Hall bar resistance as an out-of-plane field moves the up-down DW through the nanowire, underneath a nanomagnet that is magnetized in the downstream (right) or upstream (left) direction. The decrease in resistance signals the depinning of the DW from the nanomagnet site; the field at which this occurs differs by more than 10 mT for the two states.

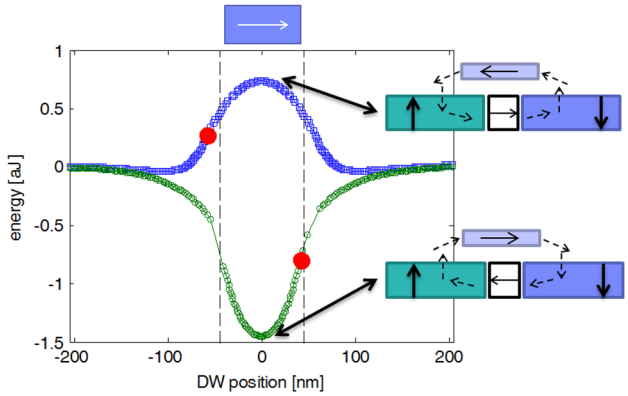

FIG. 3. Energy of the system as a function of domain wall position along the nanowire for the two nanomagnet states. The vertical dashed lines indicate the nanomagnet position along the x-axis. The graphics show the side view of the system that depict the freedom of the Néel domain wall to align itself along the nanomagnet's fringing field (dashed arrows). The solid red circles indicate the position of maximum slope, which is proportional to the depinning field.

nanomagnet is drawn. We calculated the energy of the system using OOMMF[7] for each position of the DW along the wire. The DW was allowed to evolve to its lowest energy internal magnetic structure at each position, being kept in place by a superimposed potential well by means of a tailored field. We verified that the effect of the potential well on the DW structure itself amounts to less than 0.1 aJ. Results of the micromagnetic energy calculations are shown in Figure 3 for an up-down DW in the vicinity of both right- (bottom curve) and left-magnetized (top curve) nanomagnets. It becomes apparent that the energy barrier that a DW encounters at the upstream edge of the nanomagnet in the $(\mathrm{ud}, \leftarrow)$ configuration is much lower than the one encountered by the DW at the downstream edge of the nanomagnet in the $(\mathrm{ud}, \rightarrow)$ configuration (similarly for $(\mathrm{du}, \rightarrow)$ and $(\mathrm{du}, \leftarrow)$). The depinning field is proportional to the maximum slope of the energy landscape, indicated by solid circles in Figure 3, which means $(\mathrm{ud}, \rightarrow)$ and $(\mathrm{du}, \leftarrow)$ should have higher depinning fields than $(\mathrm{du}, \rightarrow)$ and $(\mathrm{ud}, \leftarrow)$, in accordance with the experimental results.

It may be counterintuitive that there should be a difference in energy barrier height between the right- and left-magnetized states. Indeed, if the nanomagnet's magnetostatic fringing field were simply reversed (or equivalently, the magnetization in the nanowire switched), the energy would simply be negated, and the energy landscape would be perfectly antisymmetric for the two states. However, the fine structure of the DW is responsible for introducing asymmetry in the energy landscape. Given an up-down DW as in the graphics in Figure 3, the fringing field at the head and tail of a right-magnetized nanomagnet (bottom graphic) aligns with the nanowire's magnetization, resulting in low energy, but anti-aligns when the nanomagnet is left-magnetized (top graphic), resulting in high energy. Thus, the DW polarity provides an antisymmetric component to the energy landscape. The DW chirality, on the other hand, has the freedom to align itself to the in-plane component of the nanomagnet's fringing field, so it assumes a Néel wall pointed opposite to the nanomagnet state, regardless of the DW's chirality at the time of injection. Simulations demonstrate that fields less than 10 mT can change a Néel wall's chirality, while the fringing field underneath the nanomagnet is on the order of 70 mT. The resulting configuration has low energy irrespective of the nanomagnet state, forming a symmetric reduction to the energy landscape. Together, this makes the energy well deeper than the energy hill and thus the depinning field of the $(\mathrm{ud}, \rightarrow)$ and $(\mathrm{du}, \leftarrow)$ configurations higher than $(\mathrm{du}, \rightarrow)$ and $(\mathrm{ud}, \leftarrow)$.

IV. CONCLUSION

Experiments presented here demonstrate a device where the fringing field from a nanomagnet creates a pinning site for a DW within a PMA nanowire whose strength depends on the configurable magnetic state of the nanomagnet. Micromagnetic calculations show that the fine structure of the DW is responsible for this. More specifically, the freedom of the Néel wall to align itself to the nanomagnet's fringing field reduces the energy regardless of nanomagnet state in an energy landscape that is antisymmetric with respect to the DW polarity.

A nanomagnet deposited above a nanowire thus provides an alternative for a geometric pinning site, with the additional advantage that the pinning can be controlled by applying an in-plane field to the nanomagnet. If the DW is moved by an oop field that is greater than the depinning field of one nanomagnet state but smaller than that of the other state, then the state determines whether the pinning site is active or not. Thus, apart from gating magnetic DW devices, one may envision logic applications combining the magnetic state of a nanomagnet with the polarity of a DW or memory applications where a DW reads out the state of a nanomagnetic memory cell.

ACKNOWLEDGMENTS

We acknowledge Brian Hughes and See-hun Yang for their role in fabrication of the devices. This work was supported by NanoNextNL, a micro and nanotechnology program of the Dutch Government and 130 partners.

[1]D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science **309**, 1688 (2005).
[2]S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008).
[3]J. H. Franken, H. J. M. Swagten, and B. Koopmans, Nat. Nanotechnol. **7**, 499 (2012).
[4]L. O'Brien, D. Petit, E. R. Lewis, R. P. Cowburn, D. E. Read, J. Sampaio, H. T. Zeng, and A. V. Jausovec, Phys. Rev. Lett. **106**, 087204 (2011).
[5]E. Varga, G. Csaba, A. Imre, and W. Porod, IEEE Trans. Nanotechnol. **11**, 682 (2012).
[6]V. L. Mironov, O. L. Ermolaeva, E. V. Skorohodov, and A. Y. Klimov, Phys. Rev. B **85**, 144418 (2012).
[7]M. Donahue and D. Porter, "Oommf user's guide, version 1.0," *Interagency Report NISTIR 6376* (National Institute of Standards and Technology, 1999).