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Author

Vogel, A.

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Field- and current-induced domain-wall motion in permalloy nanowires with magnetic soft spots

Andreas Vogel,^{1,*} Sebastian Wintz,² Theo Gerhardt,¹ Lars Bocklage,¹ Thomas Strache,² Mi-Young Im,³ Peter Fischer,³ Jürgen Fassbender,² Jeffrey McCord,² and Guido Meier¹

¹*Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung,
Universität Hamburg, 20355 Hamburg, Germany*

²*Institut für Ionenstrahlphysik und Materialforschung,
Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany*

³*Center for X-ray Optics, Lawrence Berkeley National Laboratory, 94720 California, USA*

Abstract

We study field- and current-induced domain-wall motion in permalloy nanowires comprising a square-shaped magnetically softened region. Implantation of chromium ions is used to induce pinning sites via a local reduction of the saturation magnetization. Micromagnetic simulations, magnetic transmission soft X-ray microscopy, and electrical measurements are employed to characterize the pinning potential which significantly differs for transverse and vortex walls. Reliable domain-wall depinning from a so-called magnetic soft spot by single current pulses is observed. This demonstrates the suitability of these pinning sites for applications.

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*Electronic address: andreas.vogel@physnet.uni-hamburg.de

New concepts of high-density and ultrafast nonvolatile data storage devices involve the controlled motion of magnetic domain walls (DWs) in nanowires [1–3]. To realize such a device, reproducible and reliable pinning sites for individual DWs are required. Geometric constrictions are widely used to create local confining potentials that act as pinning sites for individual DWs [4–10]. As an alternative, the local modification of magnetic properties by ion irradiation is suitable to induce pinning sites [11]. In this case, a variation of the wire geometry on the nanoscale is not required. Implantation of chromium ions into permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) causes alloying and structural defects which lead to a reduction of the Curie temperature and the saturation magnetization M_S as well as to small changes of the magnetocrystalline anisotropy [12–14]. Field-driven pinning and depinning of a DW at these so-called magnetic soft spots has been directly observed by magnetic transmission soft X-ray microscopy (MTXM) [11]. The strength of the pinning potential can be tuned by the chromium ion fluence applied to induce the soft spots.

Potential storage devices, e.g., the racetrack memory [2] necessitate to move a series of DWs. Neighboring head-to-head and tail-to-tail DWs in a nanowire move in opposite directions under application of uniform magnetic fields and annihilate each other. The manipulation of magnetic configurations by spin-polarized currents via transfer of spin-angular momentum [15], however, opens the possibility to move these DWs in the same direction. In the absence of an external magnetic field, the DWs are displaced in the direction of the electron flow [2, 4, 16, 17].

Here, we study the field- and current-induced depinning of DWs from a square-shaped magnetic soft spot in permalloy nanowires. Micromagnetic simulations, high resolution MTXM, and electrical measurements of the anisotropic magnetoresistance are employed to characterize the pinning potential. Depinning probabilities are determined for different amplitudes of single current pulses driven through the wire.

Micromagnetic simulations of the propagation of a DW driven by an external magnetic field are performed using the Object Oriented MicroMagnetic Framework (OOMMF) [18]. We consider a 200 nm wide and 15 nm thick nanowire comprising a transverse wall and a 400 nm wide and 30 nm thick nanowire comprising a vortex wall. A saturation magnetization $M_S = 8.6 \times 10^5 \text{ Am}^{-1}$ and an exchange constant $A = 13 \times 10^{-12} \text{ Jm}^{-1}$ are assumed. The Gilbert damping parameter is set to $\alpha = 0.5$ which leads to a smooth propagation of the DW through the wire during the calculations and, in this way, enables to evaluate the

FIG. 1: (Color online) Micromagnetic simulation of the position-dependent total energy E_{tot} (solid line) for a (a) transverse and (b) vortex wall in a nanowire. The soft magnetic region is marked by the turquoise shadow. The dashed line (left axis) represents the demagnetization energy E_d and the dotted line (right axis) represents the exchange energy E_{ex} . Insets show the DW structure in the corresponding regions. Energy values are normalized to the total energy in the initial state (left insets). (c)-(e) Successive differential X-ray micrographs of the magnetization configuration under application of a magnetic field aligned parallel to the nanowire. Arrows indicate the magnetization direction.

potential. The saturation magnetization in the region of the magnetic soft spot is 80% of the original value [19]. Figures 1(a) and 1(b) show different potentials for transverse and vortex walls. The normalized total energy E_{tot} associated with the transverse wall is locally reduced (potential well) and a position of the DW at the magnetic soft spot is thus energetically favorable in comparison to the environment. For a vortex wall, the total energy also decreases approaching the soft spot but the soft spot itself represents a potential barrier for the DW. The insets indicate that the vortex structure is pinned at the border of the spot. Note that, in both cases, the relative contribution of the exchange energy E_{ex} to the total energy is about 14%. A change of the exchange constant in the soft magnetic region is not considered and the decrease of E_{ex} in Fig. 1 is attributed to a change of the structure of the DW, compare insets of Figs. 1(a) and 1(b).

Nanowires with a width of 400 nm are fabricated using electron-beam lithography and

FIG. 2: (Color online) Scanning-electron micrograph of a 400 nm wide permalloy nanowire with gold contacts L1 and L2. The position of the magnetic soft spot is marked by a turquoise shadow. The electron pulse and the field angle φ are indicated.

lift-off processing. Polycrystalline permalloy with a thickness of 30 nm is thermally evaporated onto 100 nm thin silicon nitride membranes and silicon substrates with a 300 nm thick silicon oxide coating. A magnetic soft spot is induced by 15 kV chromium ion irradiation at a fluence of $1.5 \times 10^{16} \text{ cm}^{-2}$ through a PMMA electron-beam resist shadow mask. Before irradiation, the shadow mask is covered with 3 nm chromium to reduce sputtering effects.

Magnetic transmission soft X-ray microscopy enables to directly image the position of a DW. Measurements are performed at beamline 6.1.2 of the Advanced Light Source in Berkeley, CA, USA [21] using the sample design with a rectangular nucleation pad described in Ref. [11]. The sample is mounted under an angle of 60° with respect to the beam propagation direction. Magnetic contrast is provided via the X-ray magnetic circular dichroism (XMCD) at the Ni L_3 -absorption edge (852.7 eV) [22]. Figure 1(c) shows a MTXM micrograph in the saturated state. A magnetic field aligned parallel to the nanowire is successively reversed. Differential images with respect to the saturated state are shown in Figs. 1(d) and 1(e) for two characteristic magnetization configurations. White contrast in Fig. 1(d) reveals that at 14.4 mT a DW is pinned at the boundary of the magnetic soft spot as anticipated from the micromagnetic simulations for a vortex wall. Note that for the given wire geometry, the presence of a vortex wall is energetically favorable [9, 20]. In Fig. 1(e), the DW is depinned at nominally 27.0 mT which is significantly higher than the typical depinning fields from intrinsic pinning sites [11]. To further characterize the pinning potential, electrical measurements with a high repetition rate are performed.

Pinning and depinning of DWs can be electrically detected by a change of the anisotropic magnetoresistance (AMR) [9]. For this purpose, nanowires as shown in Fig. 2 are contacted via two gold leads. By applying an external magnetic field of 120 mT under an angle of

FIG. 3: Dependence of the resistance of a nanowire between the contacts L1 and L2 on a magnetic field in x direction. The arrow indicates the sweep direction of the magnetic field. (a)-(c) Tail-to-tail or (d)-(f) head-to-head DWs have been prepared in the curvature of the wire prior to the field sweep.

$\varphi = -100^\circ$ with respect to the x axis, a tail-to-tail DW is prepared in the curvature of the wire. The field is switched off and then applied along the x axis to move the DW toward the soft spot. Figure 3(a) shows measurements of the resistance of the wire for a field swept in positive x direction. At 2.4 mT, the DW enters the region between the contacts and is pinned at the soft spot which can be detected as a drop of the AMR signal of about 160 mΩ. The DW is depinned at a field of 11 mT where the resistance again increases. To characterize the pinning potential, the DW is moved to the soft spot using a field of 8 mT. Subsequently, the magnetic field is swept in both directions along the x axis starting from zero field. Figures 3(b) and 3(c) reveal that the depinning field is significantly lower when the DW is pushed back toward the curvature. This indicates a potential barrier and coincides with the micromagnetic simulations for a vortex wall and the results of the MTXM measurements where the DW is pinned at one side of the soft spot, compare Fig. 1(d). Repeated measurements reveal a narrow depinning field distribution which indicates that the same DW type is reproducibly achieved. In Figs. 3(d)-3(f) measurements for a head-to-head DW are shown. In this case, the DW is prepared by applying the field under an angle of $\varphi = 82^\circ$.

FIG. 4: (Color online) Depinning probability of a tail-to-tail DW for different amplitudes of a 10 ns current pulse and different magnetic background fields (11070 measurements).

The absolute depinning fields are almost equal to the fields observed for the tail-to-tail DW.

To investigate the current-driven depinning, single 10 ns voltage pulses with a rise time of 2 ns are driven through the wire between the contacts L1 and L2. The AMR is measured (i) after creation of the DW in the curvature, (ii) after moving the DW toward the soft spot, and (iii) after application of the pulse. Figure 4 shows the depinning probability of a tail-to-tail DW for pulses of different amplitudes at magnetic background fields between 8 and 11 mT. Measurements have been repeated 10 times for each set of parameters. Note that events where no DW was pinned at the spot before application of the pulse are not taken into account to calculate the depinning probability. A negative pulse amplitude corresponds to an electron flux in the direction of the DW motion given by the background field. Above a certain threshold value, the DW is depinned by the resulting current pulse. For smaller background fields, higher current densities are required. At a pulse amplitude of $V_0 = \pm 1.3$ V, a maximum current density of $j \approx 1 \times 10^{12}$ Am⁻² is achieved. Here, the critical current density is higher when the direction of the electron flux opposes the direction of the DW motion.

In summary, we have demonstrated field-induced DW pinning and depinning as well as reliable depinning by single current pulses in a permalloy nanowire comprising a square-shaped magnetically softened region. Micromagnetic simulations show different shapes of the pinning potential for transverse and vortex walls. Experimental results reveal the presence of a potential barrier which coincides with the expectations from simulations for a vortex wall. The local modification of magnetic properties by irradiation with chromium ions is suitable to induce pinning sites. Lower requirements on the lithography in compari-

son to geometric constrictions on the nanoscale, a smaller distribution of properties due to parallel processing during implantation, and fine tunability of the pinning potential via the chromium ion fluence make the magnetic soft spots a promising candidate for applications.

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- [1] D. A. Allwood *et al.*, Science **309**, 1688 (2005).
 - [2] S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008).
 - [3] T. Ono *et al.*, Science **284**, 468 (1999).
 - [4] C. K. Lim *et al.*, Appl. Phys. Lett. **84**, 2820 (2004).
 - [5] M. Kläui *et al.*, Phys. Rev. Lett. **94**, 106601 (2005).
 - [6] M. Hayashi *et al.*, Phys. Rev. Lett. **97**, 207205 (2006).
 - [7] L. K. Bogart *et al.*, Phys. Rev. B **79**, 054414 (2009).
 - [8] M.-Y. Im *et al.*, Phys. Rev. Lett. **102**, 147204 (2009).
 - [9] L. Bocklage *et al.*, Phys. Rev. Lett. **103**, 197204 (2009).
 - [10] D. Djuhana *et al.*, Appl. Phys. Lett. **97**, 022511 (2010).
 - [11] A. Vogel *et al.*, IEEE Trans. Magn. **46**, 1708 (2010).
 - [12] J. Fassbender *et al.*, Phys. Rev. B **73**, 184410 (2006).
 - [13] L. Folks *et al.*, J. Phys. D **36**, 2601 (2003).
 - [14] J. Fassbender and J. McCord, J. Magn. Mag. Mat. **320**, 579 (2008).
 - [15] S. Zhang and Z. Li, Phys. Rev. Lett. **93**, 127204 (2004).
 - [16] A. Yamaguchi *et al.*, Phys. Rev. Lett. **92**, 077205 (2004).
 - [17] G. Meier *et al.*, Phys. Rev. Lett. **98**, 187202 (2007).
 - [18] <http://math.nist.gov/oommf/>.

- [19] Broadband ferromagnetic resonance measurements on 30 nm thick permalloy films irradiated with a chromium fluence of $1.5 \times 10^{16} \text{ cm}^{-2}$ at 15 kV reveal a reduction of M_S of about 20%.
- [20] Y. Nakatani, A. Thiaville, and J. Miltat, J. Magn. Mag. Mat. **290**, 750 (2005).
- [21] P. Fischer *et al.*, Mater. Today **9**, 26 (2006).
- [22] C. T. Chen *et al.*, Phys. Rev. B **42**, 7262 (1990).

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