SCIENTIFIC REPORTS

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SUBJECT AREAS:
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IMAGING TECHNIQUES

Received
18 December 2012

Accepted
15 April 2013

Published
26 April 2013

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Time-resolved imaging of nonlinear magnetic domain-wall dynamics in ferromagnetic nanowires

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In ferromagnetic nanostructures domain walls as emergent entities separate uniformly magnetized regions. They are describable as quasi particles and can be controlled by magnetic fields or spin-polarized currents. Below critical driving forces domain walls are rigid conserving their spin structure. Like other quasi particles internal excitations influence the domain wall dynamics above a critical velocity known as the Walker breakdown. This complex nonlinear motion has not been observed directly. Here we present direct time-resolved x-ray microscopy of structural transformations of domain walls during motion. Although governed by nonlinear dynamics the displacement of the wall on the observed time scale can still be described by an analytical model. Using a reduced dynamical domain-wall width the model enables us to determine the mass of a vortex wall experimentally. Further we observe the creation and the mutual annihilation of domain walls. The intrinsic nanometer length and nanosecond time-scales are determined directly.

By the proposals of magnetic domain wall based logic-[1] as well as memory devices[2] and the technical application in sensors[3] the interest in domain walls has significantly increased[4]. In these devices spin-polarized electric currents and magnetic fields are used to shift domain walls through nanowires. In a magnetic field the velocity of rigid domain walls is proportional to the driving field[5] until it reaches the Walker breakdown where it is slowed down due to internal excitations[6]. To study the motion of domain walls the Oersted field of current pulses has been used[7–10] to create walls in technical relevant geometries[2]. Even though most studies focus on the wall motion below the Walker breakdown the creation requires high Oersted fields[11,12] leading to an initial motion of the domain walls above the breakdown. Wall transformations have been verified indirectly by resistance measurements[13] and magnetic imaging has provided static information on the domain wall structure[14–16]. For applications[2] a fast and reliable domain wall generation is mandatory. Direct observation of the process on genuine time- and length scales is essential for understanding this mechanism.

We use time-resolved scanning transmission X-ray microscopy (STXM, see methods) to observe the creation and the motion of domain walls with sub-nanosecond time and 25 nm spatial resolution[17]. Domain walls are created by current pulses through a stripline crossing a permalloy nanowire as shown in Fig. 1a. The pulse is accompanied by an Oersted field of 66 mT creating two domain walls underneath the stripline. Both walls move away from the stripline into opposite directions predominantly driven by the in-plane component of the Oersted field (Fig. 1c). Vortex domain walls are energetically favored in the presented wires[18] and lead to a black/white contrast in the X-ray micrographs as seen in Fig. 1b. The initial magnetization of the wire is achieved by sending a second inverted current pulse through the stripline to again create two domain walls. These collide with the primarily created domain walls from the first pulse and annihilate each other as schematically shown in Fig. 1c. As the Oersted field of the second pulse points in the direction of the initial magnetization the initial state of the wire is restored.

Results

Fast domain wall creation by an Oersted field. The creation of two domain walls by a 6 ns long field pulse is shown in Fig. 2a. One nanosecond after the field pulse begins the magnetization below the stripline becomes significantly distorted and forms a vortex domain wall. An alternating domain pattern (black-white-black contrast from 1.7 ns to 2.3 ns) evolves by creation of a second vortex core above the white domain. As two

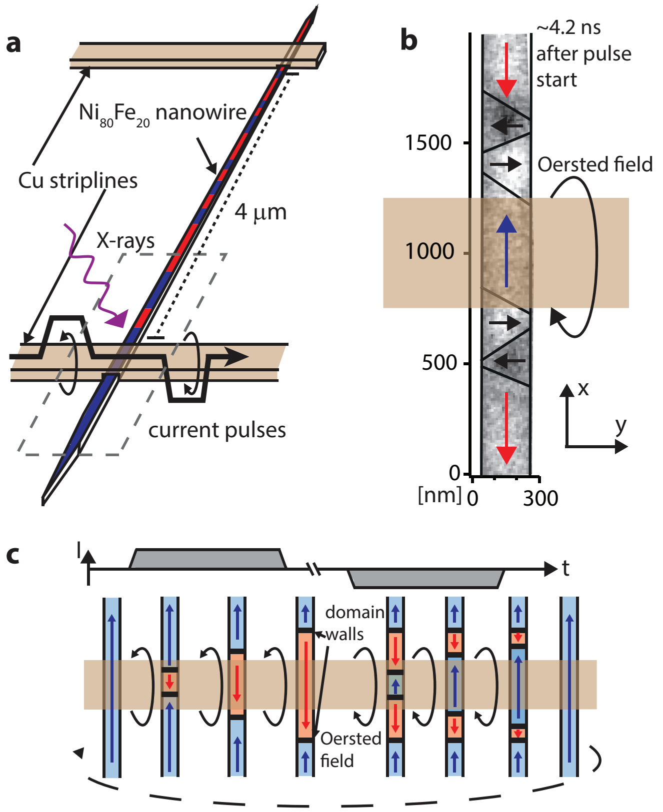

Figure 1 | Schematic views of experimental setup and measurement procedure. (a), Alternatingly magnetized nanowire with two crossing striplines to create and detect domain walls. (b), Scanning transmission X-ray microscopy superimposed with a scheme of the nanowire with two vortex domain walls in the vicinity of the lower stripline. (c), Illustration of the repeated process for time-resolved imaging. A field pulse creates one domain wall at the upper and one at the lower edge of the stripline. The succeeding domain walls from the second pulse annihilate the ones created by the first pulse therefore resetting the nanowire to its initial state.

distinct domain walls emerge their description as quasi particles becomes plausible. After separation the two domain walls take on a more transverse wall like structure where the vortex core is not visible anymore (2.6 ns to 2.9 ns) before transforming back into vortex walls (black/white and white/black contrast from 3.4 ns to 4.6 ns). The macroscopic motion of the domain wall is almost linear up to this point. After 4 ns the domain wall decelerates and the vortex core moves back towards the stripline by increasing the size of the outer transverse part of the domain-wall and decreasing the inner ones (4.6 ns to 5.7 ns) until the current pulse ends and the domain wall relaxes into a stable vortex wall (5.7 ns to 8.0 ns). This oscillation of the domain-wall width as well as the vortex core oscillation along the propagation direction of the wall have been theoretically predicted above the Walker breakdown[19]. As the current pulse is applied a fraction of the current is transmitted through the nanowire. The current causes an additional force on the upper wall via spin-transfer torque thus most likely leading to the difference in velocity of the upper and the lower domain wall.

Mutual annihilation of domain walls. In Fig. 2b the consecutive second domain wall creation leading to the mutual annihilation of all domain walls is shown. At the beginning of the second pulse only the primarily created domain walls are present within the wire (0.3 ns to 1.1 ns) until two new domain walls with opposite chirality compared to the initial walls are created (1.4 ns to 2.3 ns, see Fig. 1c). The magnetization between the new domain walls points in the same direction as the magnetization outside the first domain walls. The two walls on each side of the stripline collide and the vortex core of the outer domain wall gets pulled towards the stripline before the walls mutually annihilate each other (3.1 ns to 5.7 ns). The attraction occurs by the time the two vortices are 500 nm apart and the transverse parts of the walls merge. By the time the 6 ns long pulse is over the initial magnetization is restored. Although the domain walls collide about 3 ns after the Oersted field is present the final relaxation of the magnetization takes another 3 ns (light black and white contrast until 6.3 ns).

Analytical description. The almost constant velocity of the domain wall within the first nanoseconds after its creation is also visible in the averaged domain-wall positions in Fig. 3. The motion directly correlates with the spatially varying inplane component of the Oersted field shown on the right. The domain wall moves with high velocities until the edge of the stripline is reached and the magnetic field rapidly drops. The 66 mT field underneath the stripline is far above the Walker breakdown field and therefore leads to the observed transformations from transverse to vortex walls and domain wall width oscillations in Fig. 2. Next to the stripline where the field decreases the domain wall slows down and finally stops when the inplane component of the Oersted field subsides below 3 mT which is the propagation threshold field for domain walls in our samples[11]. The theoretical description of the vortex wall-dynamics for high fields is rather complex and has been carried out in detail and compared to numerical simulations for the presented wire dimensions by Clarke et al.[19]. But although the detailed dynamics are very complex we find that the total displacement of the domain wall above the Walker breakdown can still be described by the 1D model[20]. From the equations of motion of a domain wall under the influence of a field the analytical expression

$$\ddot{X} = \frac{\lambda\gamma}{\alpha\tau_D} H_{Oer} - \frac{\dot{X}}{\tau_D} + \frac{\lambda\gamma\alpha}{1+\alpha^2}\dot{H}_{Oer} \quad (1)$$

can be derived[21]. H_{Oer} in our case is the spatially varying Oersted field and $\alpha = 0.0076$ the Gilbert damping. The damping time of the domain wall τ_D and the effective domain-wall width λ can be used to calculate a domain wall mass equivalent by

$$m = \frac{2\alpha S\mu_0 M_S \tau_D}{\lambda\gamma} \quad (2)$$

where $S = 20\ \text{nm} \times 200\ \text{nm}$ is the cross section of the wire, μ_0 is the vacuum permeability, $M_S = 8 \times 10^5$ A/m the saturation magnetization and $\gamma = \mu_0 \cdot 1.76 \times 10^{11}$ C/kg $= 2.211 \times 10^5$ m/C is the gyromagnetic ratio.

A fit of the displacement in Fig. 3 with the numerically integrated acceleration of a wall from equation 1 gives a maximum velocity of 159 m/s which is in agreement with other studies[9,13,15] and the damping time of the domain wall $\tau_D = 0.44$ ns is the same order of magnitude as in other experiments[21,22]. The acceleration of the wall is proportional to the Oersted field scaled by a domain wall width parameter λ. This parameter is only comparable in magnitude to the real wall width for transverse walls and is about one order of magnitude smaller than the real width for vortex domain walls in low fields as the vortex core magnetization strongly influences the dynamics[18,23]. The observed transformations in the spin structure for high driving fields in Fig. 2 also influence the macroscopic motion of the wall leading to a lower but also constant mobility[5]. Therefore a reduced effective domain wall width of $\lambda = 0.13$ nm is obtained. Hence the calculated mass of the vortex domain wall is $m = 4.5 \times 10^{-22}$ kg in agreement with the estimations for vortex walls in this geometry[19].

Generation and annihilation of domain walls with the same chirality. In Fig. 4a the creation of domain walls by a longer pulse

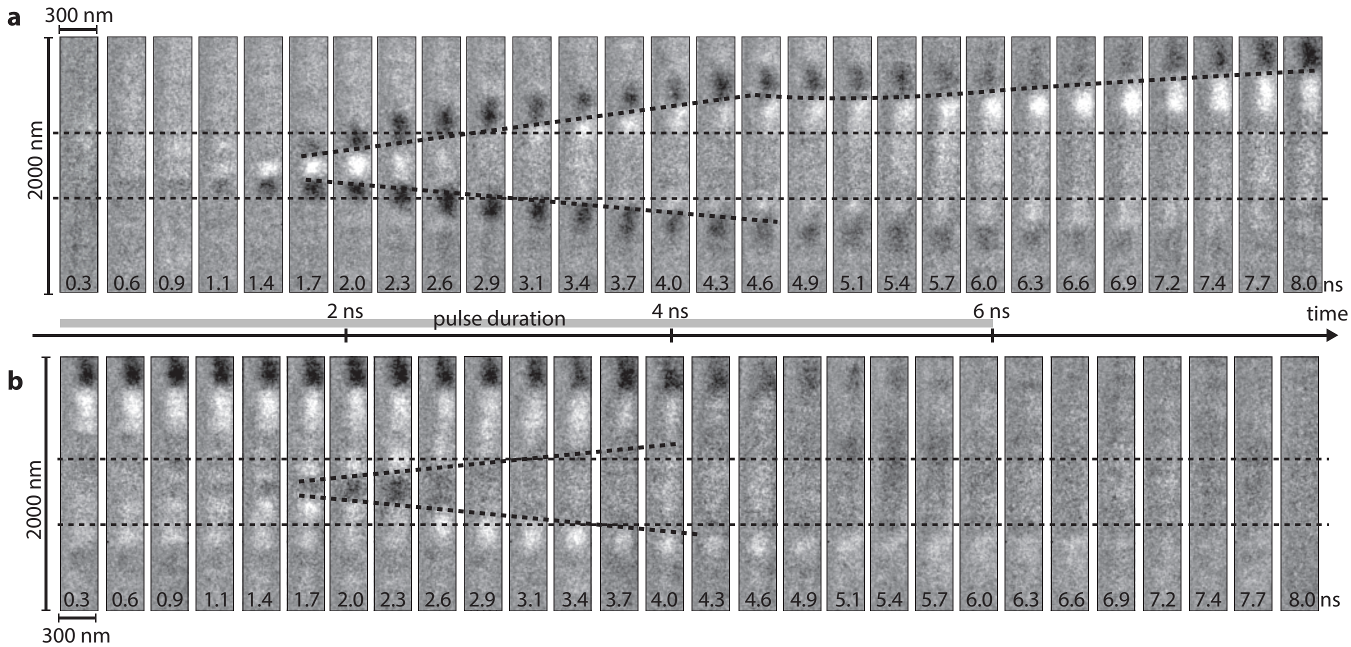

Figure 2 | Time-resolved STX micrographs in time steps of 286 ps. (a), Creation of two domain walls by the field of a current pulse through the perpendiculary aligned stripline indicated by the horizontal dotted lines. A guide to the eye for the domain wall motion is given by the dashed lines. (b), Collision of two further domain walls created by an inverted current pulse. The collision leads to an annihilation of all four walls. The chirality is opposite for the first and second creation because of the opposite current flow direction through the stripline.

of 8 ns with a lower time resolution compared to Fig. 2 is imaged. Directly after creation the upper domain wall has a black/white contrast beeing a vortex wall. After transformation to a transverse wall (3.5 ns) a vortex wall is again observed 2 ns later (5.5 ns) with the opposite white/black contrast showing that the chirality has changed. Note that the domain wall stops after the transformation even though the Oersted field is still applied because the driving field dropped below the propagation field (compare Fig. 3). In contrast to the continued motion of the non transformed wall under its own inertia (Fig. 2a) the transformation seems to supress such motion and the wall stops in the low field beyond the edge of the stripline (Fig. 4a). Although the transormation of the wall occurs after 5 ns it is not observed in the creation process with 6 ns long pulses in Fig. 2. Due to the nonideal transmission of square pulses through the setup the actual shape of the 8 ns and the 6 ns long pulse differ resulting in a not fully comparable creation process.

Since the domain wall has changed its chirality the mutual annihilation of two domain walls with the same chirality is observed in Fig. 4b where in Fig. 2b the collision of two domain walls with opposite chirality is shown. Unlike in Fig. 2 the second emerging domain wall does not attract the existing domain wall (2.0 ns to 3.0 ns) before merging into one horizontally oriented domain. This merged domain moves away from the stripline and then vanishes as the surrounding domains below and above are aligned parallel. Although the annihilation process differs from the one of two domain walls of different chirality the time scale of the process is identical.

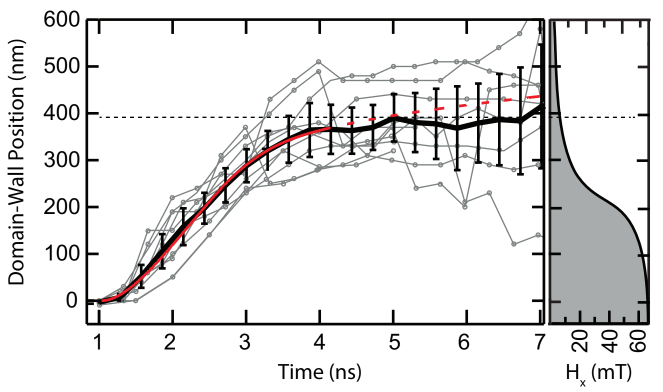

Figure 3 | Averaged domain-wall position (black solid line) with concomittant error bars relative to the center of the stripline in dependence of the time from the beginning of the current pulse. Data of ten time-resolved image sequences is shown in grey. The solid red line is a fit of the equation of motion from the 1D model and is extended in the region where the domain wall is pinned. The inplane component of the Oersted field along the wire is plotted on the right.

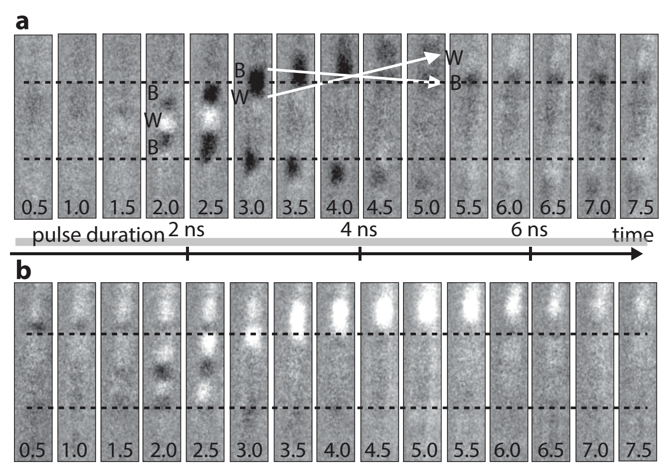

Figure 4 | STX micrographs in time steps of 500 ps. (a), Domain-wall creation by a 8 ns long field pulse with a chirality change at the end of the creation process. The domain wall stops moving before the pulse has ended. (b), Collision of two domain walls of the same chirality due to the chirality change of the first domain wall after creation (compare fig. 2 (b)).

Discussion

In summary we have shown temporally resolved microscopy of nonlinear motion of domain walls in high magnetic fields. Oscillations of the domain wall width and transformations of the wall between vortex and transverse spin structure were imaged on genuine time scales. Further the creation process of vortex domain walls of both chiralities as well as the mutual annihilation of domain walls with the same and with opposite chirality have been directly observed. This gives access to analysis of vortex domain-wall dynamics that are relevant for technical applications such as logic and memory devices[1,2] but have previously only been accessible by simulations and complex analytical calculations. Despite the complex processes during motion we have shown that the displacement of transforming domain walls on the observed time scale can still be described by the equations of motion from the 1D model using a reduced dynamic domain wall width. The direct observation of domain wall dynamics opens the path to reduced generation times.

Methods

Sample preparation. The samples consist of 8 μm long, 200 nm wide and 20 nm thick permalloy ($Ni_{80}Fe_{20}$) nanowires with two perpendicular striplines. The nanowires are prepared by thermal evaporation on silicon covered silicon nitride membranes. The striplines are deposited after RF cleaning of the wire and made of a Al/Au contact layer with 90 nm copper on top that is capped with 5 nm of gold. All structures were written by electron-beam lithography. Note that pulse current densities of about 10^{12} A/m^2 in the 500 nm wide and 100 nm thick striplines create an Oersted field of 66 mT directly underneath the stripline. These high current densities lead to a problematic Joule heating when the structures are prepared on silicon nitride membranes[24]. Therefore an additional silicon layer was deposited on the membranes before preparation as the cooling is greatly improved on silicon. For pulse generation the pulse pattern generator Agilent 81134A with risetimes below 100 ps was used.

Time-resolved microscopy. Imaging was done with the MAXYMUS microscope (Beam-line UE46 PGM-2 at BESSY II synchrotron in Berlin, Germany). The sample is tilted by 30 degrees around the x-axis. Therefore a horizontal magnetization in the sample has components parallel to the beam axis and gives x-ray magnetic circular dichroism (XMCD) contrast at the Ni-L_3 edge. Consequently the spin structure of the domain walls can be observed but not the domains themselves. This leads to a black/white contrast of vortex domain walls as shown in Fig. 1b. To image the magnetization dynamics in time steps of 500 ps down to 286 ps the processes are repeated to accumulate multiple synchrotron flashes to obtain a reasonable contrast. Therefore the initial magnetization of the wire has to be restored within nanoseconds. The process is repeated for imaging with a repetition rate of several MHz by asynchronous excitation. The image contrast of the stopped upper domain wall compared to the lower wall is significantly higher presumably caused by a more dominant pinning at a specific minor fault in the nanowire above the stripline. This leads to a higher reproducibility of the process especially in the region where the domain wall stops.

1. Allwood, D. A. *et al.* Magnetic Domain-Wall Logic. *Science* **309**, 1688 (2005).
2. Parkin, S. S. P., Hayashi, M. & Thomas, L. Magnetic Domain-Wall Racetrack Memory. *Science* **320**, 190 (2008).
3. Mattheis, R., Glathe, S., Diegel, M. & Hübner, U. Concepts and steps for the realization of a new domain wall based giant magnetoresistance nanowire device: From the available 24 multiturn counter to a 2^{12} turn counter. *J. Appl. Phys.* **111**, 113920 (2012).
4. Marrows, C. H. & Meier, G. Domain wall dynamics in nanostructures. *J. Phys.: Condens. Matter* **24**, 020301 (2012).
5. Beach, G. S. D., Nistor, C., Knutson, C., Tsoi, M. & Erskine, J. L. Dynamics of field-driven domain-wall propagation in ferromagnetic nanowires. *Nat. Mater.* **4**, 741 (2005).
6. Schryer, N. L. & Walker, L. R. The motion of 180 domain walls in uniform dc magnetic fields. *J. Appl. Phys.* **45**, 5406 (1974).
7. Hayashi, M. *et al.* Current Driven Domain Wall Velocities Exceeding the Spin Angular Momentum Transfer Rate in Permalloy Nanowires. *Phys. Rev. Lett.* **98**, 037204 (2007).
8. Beach, G. S. D., Knutson, C., Nistor, C., Tsoi, M. & Erskine, J. L. Nonlinear Domain-Wall Velocity Enhancement by Spin-Polarized Electric Current. *Phys. Rev. Lett.* **97**, 057203 (2006).
9. Jiang, X., Thomas, L., Moriya, R. & Parkin, S. S. P. Discrete Domain Wall Positioning Due to Pinning in Current Driven Motion along Nanowires. *Nano Lett.* **11**, 96 (2011).
10. Muñoz, M. & Prieto, J. L. Suppression of the intrinsic stochastic pinning of domain walls in magnetic nanostripes. *Nat. Comm.* **2**, 562 (2011).
11. Stein, F.-U., Bocklage, L., Matsuyama, T. & Meier, G. Generation and annihilation of domain walls in nanowires by localized fields. *Appl. Phys. Lett.* **100**, 192403 (2012).
12. O'Brien, L., Read, D., Petit, D. & Cowburn, R. B. Dynamic propagation and nucleation in domain wall nanowire devices. *J. Phys.: Condens Matter* **24**, 024222 (2012).
13. Hayashi, M., Thomas, L., Rettner, C., Moriya, R. & Parkin, S. S. P. Direct observation of the coherent precession of magnetic domain walls propagating along permalloy nanowires. *Nat. Phys.* **3**, 21 (2007).
14. Yamaguchi, A. *et al.* Real-Space Observation of Current-Driven Domain Wall Motion in Submicron Magnetic Wires. *Phys. Rev. Lett.* **92**, 077205 (2004).
15. Meier, G. *et al.* Direct Imaging of Stochastic Domain-Wall Motion Driven by Nanosecond Current Pulses. *Phys. Rev. Lett.* **98**, 187202 (2007).
16. Kläui, M. *et al.* Direct Observation of Domain-Wall Configurations Transformed by Spin Currents. *Phys. Rev. Lett.* **95**, 026601 (2005).
17. Ade, H. & Stoll, H. Near-edge X-ray absorption fine-structure microscopy of organic and magnetic materials. *Nat. Mater.* **8**, 281 (2009).
18. Nakatani, Y., Thiaville, A. & Milat, J. Head-to-head domain walls in soft nano-strips: a refined phase diagram. *J. Magn. Magn. Mater.* **290**, 750 (2005).
19. Clarke, D. J., Tretiakov, O. A., Chern, G.-W., Bazaliy Ya. B. & Tchernyshyov, O. Dynamics of a vortex domain wall in a magnetic nanostrip: Application of the collective-coordinate approach. *Phys. Rev. B* **78**, 134412 (2008).
20. Krüger, B., Pfannkuche, D., Bolte, M., Meier, G. & Merkt, U. Current-driven domain-wall dynamics in curved ferromagnetic nanowires. *Phys. Rev. B* **75**, 054421 (2007).
21. Bocklage, L. *et al.* Dependence of Magnetic Domain-Wall Motion on a Fast Changing Current. *Phys. Rev. Lett.* **103**, 197204 (2009).
22. Bocklage, L. *et al.* Time-resolved imaging of current-induced domain-wall oscillations. *Phys. Rev. B* **78**, 180405 (2008).
23. Thomas, L. *et al.* Oscillatory dependence of current-driven magnetic domain wall motion on current pulse length. *Nature* **443**, 197 (2006).
24. Fangohr, H., Chernyshenko, D. S., Franchin, M., Fischbacher, T. & Meier, G. Joule heating in nanowires. *Phys. Rev. B* **84**, 054437 (2011).

Acknowledgements

We thank Ulrich Merkt for persistent support and fruitful discussions and Toru Matsuyama, Michael Volkmann and Michael Bechtel for excellent technical support as well as Stefan Rößler and Sebastian Hankemeier for providing silicon films. Financial support by the Deutsche Forschungsgemeinschaft via Sonderforschungsbereich 668 and via Graduiertenkolleg 1286 is gratefully acknowledged. This work has been supported by the excellence cluster 'The Hamburg Centre for Ultrafast Imaging - Structure, Dynamics, and Control of Matter on the Atomic Scale' of the Deutsche Forschungsgemeinschaft.

Author contributions

Sample preparation: F.-U.S. and L.B.; Experiment: F.-U.S., L.B. and M.W.; Analyses: F.-U.S. and L.B.; Manuscript: F.-U.S., L.B. and G.M.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Stein, F.-U., Bocklage, L., Weigand, M. & Meier, G. Time-resolved imaging of nonlinear magnetic domain-wall dynamics in ferromagnetic nanowires. *Sci. Rep.* **3**, 1737; DOI:10.1038/srep01737 (2013).