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Shape critical properties of patterned Permalloy thin films

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Abstract

The effects of shape and edges in magnetic elements with reduced dimensions on the magnetization reversal of cross- and framed cross-shaped Ni₇₉Fe₂₁ (30nm) films were studied. Remagnetization details in the stripes of the patterned structures, which had 3 μm to 30 μm widths and ~100 μm lengths, were visualized by the magneto-optical indicator film technique. The magneto-optic images revealed three different types of the domain structure formation and evolution in the samples during their magnetization reversal: (i) spin rotation with growth and annihilation of a cross-tie structure in the stripes perpendicular to the applied field, (ii) nucleation and fast motion of special boundaries, which consist of a number of coupled vortices located along both edges of the stripes parallel to the applied field, and (iii) nonuniform magnetization rotation with macrodomain nucleation and domain wall motion in the large unpatterned part of the films. It was experimentally revealed that there exists a dependence of the critical field for nucleation and motion of domain walls in the parallel-to-field stripes on their width and frame width. In particular, an inverse proportionality between this nucleation field and stripe width was found. Both experimental and simulation results show that, in cases (i) and (ii), the magnetostatic fields, which are formed on the edges of the stripes and at their intersections, play a crucial role in the formation of spin inhomogeneities and switching of the samples.

Keywords

Domain structure; Magnetic microstructure; Magneto optical imaging; Patterned thin film; Spin vortex

1. Introduction

Steady improvement of thin film growth and patterni ng techniques pushes the physical size of samples towards ever-smaller dimensions. Magnetic properties of the thin-film elements are by virtue of their small size very different from the same materials in bulk. In this case, the magnetization, **M**, distribution and reversal in thin films with restricted lateral sizes is mostly governed by the magnetostatic fields localized on their edges [1]. Manipulation of the size, shape, and orientation of the patterned thin films with a thickness the Bloch wall width results in films possessing unusual properties [1–5]. Of fundamental interest is a precise knowledge of the 2D-dimensional surface magnetic structure and its evolution with

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field, $\mathbf{H}$, application, and their dependence on the shape and size of these small magnetic elements.

In recent years, magnetic thin films patterned at the nanometer scale have become attractive for applications in magnetic random access memory (MRAM) with increased storage density [6, 7], magnetic field sensors [8], spin transistors [7, 9], and other devices. The most widely studied shape of thin-film elements has been rectangular and cross-shaped, due largely to the applicability of such structures to MRAM [6, 7] and magnetic field sensors [8]. But there have also been studies of circular magnetic elements [10, 11]. When the size of the magnetic structures becomes of the same order of magnitude as some characteristic magnetic length scale (domain wall thickness, magnetic exchange length, spin vortex width, and other stable or unstable magnetic perturbation sizes), or when the magnetic entities interact with each other, the dipolar interactions within the elements give rise to a configurational anisotropy and to a change in the coercivity. In this case, the size and geometrical configuration of the elements have caused modifications in their domain structure and play a significant role in controlling its evolution upon application of a magnetic field [1–4, 10, 12–16].

In particular, it was established there is a significant influence of shape and size on the hysteresis loops [3, 16] and configurational anisotropy [3, 4] in Permalloy thin nanostructures. In recent years, a few Kerr microscopy, magnetic force microscopy, and micromagnetic simulation studies have been conducted on the fabrication and characterization of planar magnetic microstructures fabricated as rectangles [1, 2, 4, 12, 13, 16] and crosses [12, 14, 15] of sizes ranging from tens of nanometers to tens of micrometers. It was shown in these studies that the ground state (e.g., at $H=0$) of such thin-film elements may consist of one or a number of complicated domain structures including vortices and antivortices, “diamond” and Landau structures, and cross-tie structures. Such magnetic states are determined by the minimization of magnetostatic, exchange, and anisotropy energies which depends on the size, shape, orientation, thickness, and composition of the structures.

However, despite the previous detailed experimental and theoretical investigations of the shape and size influence on the ground state of restricted thin magnetic films, the size and shape dependence of the dynamics of the domain structure transformation upon application of a field has not been studied sufficiently. Recently, new features of the magnetization reversal in both free and exchange-coupled (with an antiferromagnet IrMn layer on top) thin ferromagnetic (FM) $\text{Ni}_{79}\text{Fe}_{21}$ films [17–19] patterned in the form of a square mesh were revealed. Quite different micromechanisms and switching fields of the mesh stripes were observed during magnetization reversal for $\mathbf{H}$ oriented parallel or perpendicular to the stripes. Since it is well known, the ground state and reversal mechanisms are determined by the competition from different energy sources, the difference in reversal behavior depending on the orientation of $\mathbf{H}$ was primarily due to differences in magnetostatic energy which are known to be quite large [20] in such a system. Even this study, however, did not investigate the kinetics of the transformations. In this paper, we present both experimental and simulation results of the magnetization distribution and transformation kinetics during the reversal of microstructured Py thin films. The effect of shape and edges in the magnetic

elements with reduced dimensions on the magnetization reversal of cross- and framed cross-shaped $\text{Ni}_{79}\text{Fe}_{21}$ films were studied in particular.

2. Experimental procedures and simulation

We have used Permalloy (Py) $\text{Ni}_{79}\text{Fe}_{21}$, which is almost isotropic, so any anisotropy in the laterally restricted magnetic thin films must come from their shape. Thick polycrystalline $\text{Ni}_{79}\text{Fe}_{21}$ (30 nm) films were deposited by magnetron sputtering onto Si(100) wafers having a 250 nm thermal oxide on top. The films were then microstructured into crosses with and without frames (Fig. 1) by means of optical lithography. The stripe width, b , was either 30 μm , 10 μm , or 3 μm (columns A, B, and C in Fig. 1, respectively) and the cross arms were $\sim 100 \mu\text{m}$ in length. The widths, d , of frames were either 300, 30, 10, 3, or 0 μm (rows 1, 2, 3, 4, and 5 in Fig. 1, respectively). The field used during our magnetization reversal experiments was applied along the horizontal stripes. The hysteresis loop of the whole FM film, patterned as shown in Fig. 1, was measured using a vibrating sample magnetometer. All magneto-optical (MO) measurements were performed at room temperature. Visualization of domain structures was provided during the remagnetization process using the magneto-optical indicator film (MOIF) technique [21, 22]. Real time MO imaging was made using a charge coupled device (CCD) camera capturing 30 pictures per second while H was linearly varied. In this technique, a transparent Bi-doped yttrium iron garnet indicator film with an Al mirror bottom surface is placed on top of the sample to image the stray magnetic fields around the film edges and domain walls (DWs). In the absence of a magnetic field, the garnet magnetization is oriented in-plane, but it is deflected out of plane by perpendicular components of the stray field, H , around the sample. Using a polarized light microscope with slightly uncrossed polarizer and analyzer, MO images of the sample's magnetic structure are obtained in the reflected light due to the double Faraday effect of the indicator film. The black and white colors of the MO image correspond to opposite signs of H . In order to aid the reader, throughout all the MO figures of this paper, the $\mathbf{H}$ and $\mathbf{M}$ orientations are shown by white and black arrows respectively. The magnetization configurations were also calculated using the OOMMF software code [23]. Typical material constants for Permalloy were chosen: saturation magnetization value = 860 kA/m, exchange stiffness = 13 pJ/m, and magnetocrystalline anisotropy = 0 J/m³. The discretization cell size was 30×30×30 nm³.

3. Results and discussion

Fig. 1 shows the hysteresis loop of the patterned film that was measured when the field was applied parallel to the horizontal stripe in the $\text{Ni}_{79}\text{Fe}_{21}$ crosses. The sample has a small coercivity with practically zero magnetocrystalline anisotropy and magnetostriction. For this sample which possesses only shape anisotropy, Fig. 2 shows the reversal behavior of the whole FM patterned structure having a stripe width of 30 μm . In this figure are MO images of various areas of the film, including the quasi-infinite unpatterned frame and the horizontal and vertical stripes of the patterned part of the FM film, during its remagnetization from the positive saturated state (Fig. 2a) to negative saturation (Fig. 2f). Strong MO contrast of the magneto-optic signal caused by large stray fields is observed on the vertical edges of the frame and stripes, whereas it practically vanishes at the horizontal edges. At the horizontal

edges, the magnetic field, and consequently the magnetization, are parallel to the edge and don't produce any stray field. Decreasing the external field gave rise to a decrease in the MO contrast at the vertical edges and simultaneously to a non-uniform magnetization rotation in the big open area of the frame. It also led to the formation of new monopolar (Néel) domain walls (DWs) in the vertical (perpendicular to $\mathbf{H}$) stripes (Fig. 2b). It is important to note that the black-white contrast near the new Néel walls is the same as that at the edges of the vertical stripes at saturation (Fig 2a). This means the magnetization in the left-to-right center of the Néel walls has the same orientation as it had during saturation (i.e., the initial $\mathbf{M}$ orientation). Further remagnetization of the vertical stripe occurs with $\mathbf{H}$ oriented in the opposite direction. Simultaneously in the contiguous open frame area, new macrodomains with a non-homogeneous distribution of $\mathbf{M}$ are formed (Fig. 2c), then extended (Fig. 2d, 2e), and finally disappeared (Fig. 2f) as the field is increased in the negative direction. During this change in field the Néel walls in the vertical stripe become unstable and subdomains with opposite magnetization direction appear (Fig. 2c). Subsequent spin rotation and domain wall transformation in the vertical stripe (Fig. 2d, 2e) with increasingly negative field then leads to their saturation along the new field direction (Fig. 2f). Another type of switching of the magnetization occurs in the horizontal stripe parallel to $\mathbf{H}$. This arm of the cross is mainly reversed by the formation and motion of inter-domain boundaries which nucleate on both ends near the frame (Fig. 2c,d) at a critical field H_{CR} . They then grow toward the middle very quickly (too fast to follow in our apparatus) annihilating the in-between walls when they collide (Fig. 2e). Note these boundaries are much wider, than the usual domain walls in this thin-film material, as observed by comparison with the walls in the quasi-infinite outer frame area (Fig. 2c). Only a small number of magnetization inhomogeneities were observed in this stripe during its reversal. Thus, it is obvious that the remagnetization mechanics are quite different between the continuous film and either of the stripes.

In order to exclude the influence of the domain structure of the outer frame on the magnetization reversal in the stripes, we have also observed the evolution of magnetic structure during the magnetization reversal in a cross prepared at the same time with the same sizes as in previous case, but without the frame (shown in Fig. 1 as sample 5A). Fig. 3 shows the MO images of the stripes of the FM cross, which was remagnetized from the positive (Fig. 3a) to negative (Fig. 3f) saturated state. As in the previous case, decreasing external field gives rise to a decreased MO contrast at the vertical stripe edges due to $\mathbf{M}$ rotation and leads to the formation of non-180-degree Néel domain walls (Fig. 3b), which then become practically 180-degree walls at zero field (Fig. 3c). With a reversed field increasingly applied, the domain structure variations during the magnetization reversal (Fig. 3d–3f) are similar to those described above for the vertical strip in the framed cross. However, there is a slight difference in the remagnetization of the horizontal stripe in the unframed cross. Unlike the switching of this stripe in the framed cross (Fig. 2c–2e), a large number of inhomogeneities of $\mathbf{M}$ formed preceding the fast switching of this unframed stripe (Fig. 3c–3e).

We have also examined the reversal behavior of the patterned FM structures having smaller sizes (Fig. 4 and 5). Fig. 4 shows MO images of the FM cross with $b = 10 \mu\text{m}$. during its magnetization reversal in a horizontal field. Again, strong contrast in the magneto-optic

signal caused by large stray fields, was observed on the edges of the vertical stripe and ends of the horizontal stripe in the positive saturated state (Fig. 4a). This strong contrast decreased with decreasing field (Fig. 4b) and practically vanished at $H = 0$ (Fig. 4c). However, only one 180-degree Néel domain wall in the middle of the vertical stripe is gradually formed (not shown here) and then divided by a number of subdomains (Fig. 4c, 4b) during this stage of the remagnetization. Increasingly negative fields led to an increase in the MO contrast (with reversed color) and a gradual disappearance of the subdomain structure (Fig. 4d). But another way of switching was observed for the horizontal stripe. Initially, special non-uniform areas with opposite magnetization were formed at the ends (Fig. 4c, 4d) or/and near the stripes' intersection (Fig. 4d) which then grew quickly toward the opposite ends (Fig. 4e). This switching from the positive stripe polarization (bright spot on the right, Fig. 4d) to the negative one (dark spot on the right, Fig. 4e) occurs at H_{CR} in less than 33 ms (the time between two CCD frames). It is important to note that a low MO contrast inhomogeneous modulation of $\mathbf{M}$ forms along this stripe preceding this fast switching. This inhomogeneity may be seen in the Fig. 4d inset which is an enlargement and higher contrast view of part of the $b=10\text{ }\mu\text{m}$ wide horizontal stripe just prior to its fast switching in a horizontal field. Clearly seen are the black-white domains which formed near the edges of the stripe during its remagnetization. When the negative field was increased to a large enough value, it is clear from the inverted MO contrast on the edges of the vertical stripe and ends of horizontal stripe that the sample finally ends in the negative saturated state (Fig. 4f).

Magnetization reversal of the cross with $b = 3\text{ }\mu\text{m}$ possesses a similar scenario as in the previous cases. Firstly, the MO contrast on the vertical stripe edges decreases during its remagnetization from the positive saturation state (white on the right edge), disappearing at zero field. But in this sample, no fine structure was observed inside the stripe; in its place, a black color appeared at the top end and a white color at the bottom end of the vertical stripe during this field reduction. This appearance indicates that $\mathbf{M}$ is oriented along the vertical stripe. Application of a reversed (negative) field resulted in the appearance of the inverse black-white MO contrast (black on the right) on the stripe edge as shown in Fig. 5a. This contrast means the vertical stripe was magnetized perpendicular to the edge. The second stage of the magnetization reversal in the cross consisted of the fast horizontal stripe switching at a some critical field, preceded by the nucleation of new domains at one or both opposite ends of the horizontal stripe. Usually the boundary runs too fast and we cannot possibly register it. However, sometimes, these boundaries can be pinned on small magnetic defects such as the one shown in Fig. 5b which is also slightly visible in Fig. 5a.

As shown by the experiments shown above, there are two different stages in the magnetization reversal of crosses: (i) remagnetization of the vertical stripes by spin rotation and domain structure formation over a wide range of fields and (ii) remagnetization of horizontal stripes by the nucleation and fast growth through these stripes of inhomogeneous inter-domain boundaries, which occurs in a very narrow range of fields. In the latter, the critical field H_{CR} turns out to depend on both the stripe width b and frame width d . Fig. 6 shows the dependence of the critical field H_{CR} of switching the vertical stripes on b and d . It is surprising to find a strong linear dependence of H_{CR} on the inverse of the stripe width

($1/b$) for each structure with and without an outer frame. Moreover, the slope of the line is controlled by the frame width d : the wider the frame, the smaller the angle between the line and the $1/b$ axis. It should be noted that the slope of the H_{CR} vs $1/b$ line for each structure may be a little different in different samples and in different branches of the hysteresis loop. However, in each case this dependence is practically linear. Another item which must be pointed out is that H_{CR} converges to the value of the coercive field in the hysteresis loop (here, it is about 0.32 mT) as the cross stripe width increases to infinity.

In order to understand the micromagnetic structure of patterned thin-film structures and the influence of film edges and shapes on its evolution in a magnetic field, we carried out numerical micromagnetic simulations of microstructured elements in the form of a cross and a cross with an outer frame (Fig. 7 and Fig. 8 respectively). Indeed, we found that comparison of the computed magnetization distributions to our experiments aided our interpretation of the experimental images.

Fig. 7 shows the simulated magnetization distributions in a 30 nm thick Py magnetic layer in a cross-shaped form during a magnetization reversal process. The calculations were performed using object oriented micromagnetic framework software OOMMF [23]. Micromagnetic simulations were performed for the cross with 3 μm wide stripes and 10 μm long arms. The magnetic structure in the cross was manipulated by an external magnetic field oriented along the horizontal stripe of the cross similar to our experiments described above. After magnetizing in a saturating ($\mu_0 H = 50$ mT) magnetic field, a quasi-uniform $\mathbf{M}$ distribution was obtained. A slight magnetization deviation from the field direction was in evidence only in the narrow areas near the stripe edges of the vertical arms perpendicular to $\mathbf{H}$ and ends of horizontal arms parallel to $\mathbf{H}$.

These areas have extended due to spin rotation to lining up along the vertical direction after the field was decreased to a certain value (Fig. 7a). It is noted that the direction of this rotation is indeterminate. The magnetic spins along each vertical edge may be canted clockwise (CW) or counter clockwise (CCW) away from the $\mathbf{H}$ direction. The choice is determined by the magnetic history of the sample, and it determines the reversal micromechanisms and types of domain structures. On the one hand, when spins near the opposite edges are canted in the opposite directions (e.g., CW near the left edge and CCW near the right edge in the bottom vertical arm in Fig. 7a), 180-degree Néel domain walls in the vertical stripes are formed after $\mathbf{H}$ is reduced to zero and increased in the opposite direction (Fig. 7b). Such DWs were experimentally observed in the vertical arms of the thin-film cross 5B (Fig. 4b).

Initially, the magnetization in the Néel wall lies in the initial direction, along the $\mathbf{H}$ direction, as can be seen in Fig. 7a. On field decrease, this DW becomes unstable. Subdomains with opposite magnetization direction appear in the wall (Fig. 4b,c and Fig. 7b) forming a cross-tie structure. As shown in [19] this subdomain is bounded by a vortex and an antivortex [1]. The generation of further subdomains reaches an energetically stable density at some negative field. Further remagnetization of the vertical arms occurs with $\mathbf{H}$ directed in the opposite direction. With increasing value of the negative field, the new subdomains increase in size with the simultaneous spin rotation in the domains toward $\mathbf{H}$.

Unstable old subdomains then disappear (Fig. 4c–f, Fig. 7b,c) and with a large enough negative field (Fig. 4f) the vertical stripe becomes magnetized homogeneously in the negative field direction.

Note that the subdomain structure nucleation fields and cross-tie density can be different at different places in the sample (Fig. 4b,c). In some vertical stripes, double domain walls may even form (Fig. 3b,c). The magnetization reversal of such stripes proceeds in the same way as described above. However, in the wider vertical stripes (Fig. 2c, Fig. 3d) this process in the thin-film crosses was followed by the formation of large domains in crosses. It is also important to note that the magnetization reversal scenario described above occurs in both hysteresis loop branches, in the case when the magnetic field is oriented perpendicular to the stripe. If the field deviates from this direction by even 3 degrees – 5 degrees, the reversal of the vertical stripes occurs through quasi-homogeneous magnetization rotation.

On the other hand, when spins near the opposite edges of the vertical stripe are canted in the same direction, 180-degree Néel DWs in the vertical stripes are not formed after $\mathbf{H}$ is reduced to zero. Contrary to the previous case, in this situation all the spins in the vertical arms rotate in order to be arranged along the long edges of these arms. The final homogeneous state with all spins aligned vertically does not produce any stray field at the right and left edges and, consequently, cannot provide a MO signal at these edges. Thus, the absence of any MO signal along the vertical edges in the 3 nm cross, sample 5C, at $\mathbf{H}=0$ indicates the vertical arms are homogeneously magnetized along the vertical direction.

Fig. 7 demonstrates the results of a computer simulation of the horizontal stripe reversal as well. It reveals another key micromechanism in the magnetization switching of these arms. In saturated stripes (Fig. 7a) there are no stray fields along their edges. So, there is no reason for easy nucleation of new domains along these edges. The nucleation of domain boundaries during reversal, therefore, usually occurs near the ends of the stripe where the stray fields induce a state with some spins canted away from the $\mathbf{H}$ direction (Fig. 7b). For reversal from this ground state, such boundaries can also be formed near the intersections. These intersections can also serve as centers for boundary pinning as well. As one can see in Fig. 7c, the boundaries, which have moved from the ends, reach the intersection and transform their structure. Further increase in the negative field amplitude gives rise to the fast motion of a boundary along the horizontal arms, thereby switching their spins into the direction of the reversed field (Fig. 7d). Just prior to the fast switching, micromagnetic computations show a very complicated magnetization structure inside these arms. The $\mathbf{M}$ distribution in the horizontal stripe is shown in detail in the inset of Fig. 7c. It is clearly seen that this excited state inside the horizontal stripes consists of spin vortices (their cores are indicated by yellow cycles) with opposite chirality near opposite edges and adjacent antivortices (their cores are indicated by green cycles). In such a vortex-antivortex magnetization configuration magnetic vectors change their direction only in the middle of the stripe. Whereas the orientation of $\mathbf{M}$ near the horizontal edges hasn't changed. This observation means that spin rotation in the horizontal stripe is energetically more preferable in the middle of the stripe than near the edges. So, the competition between magnetostatic, exchange, and Zeeman energies has dictated this complicated domain boundary structure during the magnetization reversal of a thin film of anisotropy-free patterned Py. This result mimics the

observed black-white domain pattern (inset of Fig. 4d), which were formed in the horizontal stripe of the 10 μm cross sample during its remagnetization.

It should be noted that the boundaries start to run through horizontal arms after the field reaches a certain critical value of the negative field, H_{CR} . Simulation results reveal that reversal of this arm stems from the generation of the vortex-type structure near the ends or intersection of the stripes which then effectively move by the formation of new spin churning at the front of the boundary and disappearance of old vortices at the boundary tail. Therefore the boundary formation and motion depend on the total system energy, which includes the magnetostatic energy, the exchange energy, and the Zeeman energy. In this case, the minimum of the energy depends essentially on the competition of the magnetostatic and exchange energies. It is intuitively apparent that the magnetostatic energy contribution to the total energy will decrease with increasing horizontal stripe width. So, that may explain the inverse proportionality between the critical field H_{CR} of the boundary nucleation and the horizontal stripe width which was found experimentally (Fig. 6).

In order to understand the unusual influence a frame width has on H_{CR} in the framed cross, which was experimentally discovered here (Fig. 6), we conducted a simulation of such a thin-film Py element (Fig. 8). The geometric parameters of the cross were the same as in the previous case, and the width d of the frame was 3 μm . Numerical calculation shows that in saturated horizontal stripes (Fig. 8a) there is no stray field near their ends. However, a domain structure, which formed in the frame near the cross ends after field reduction to zero, assists (left side of frame on Fig. 8b) or impedes (right side of frame on Fig. 8b) the nucleation of the boundary in the horizontal arm. In this simulation, the boundary runs through the arm from the left side to the right side (Fig. 8c, d). The boundary therefore is usually formed near regions where the cross connects with the peripheral frame or unpatterned film (Fig. 1). As the frame apparently plays an important role in nucleating and moving the complicated vortex packet in the horizontal stripe, it is not therefore surprising to find that some feature of the frame might be related to H_{CR} . However, why H_{CR} is inversely related to the frame width d as experimentally observed (Fig. 6) is still an open question and needs further investigation.

4. Conclusion

Both experimental observations and simulation computations of the magnetization reversal in patterned thin-film elements were performed. The effect of shape and edges in the magnetic elements with reduced dimensions on the magnetization reversal of cross- and framed cross-shaped $\text{Ni}_{79}\text{Fe}_{21}$ (30nm) films were studied using the magneto-optical indicator film technique. We have established that there are three different remagnetization modes in the Py patterned structures having cross arms with 3 μm – 30 μm widths and ~100 μm lengths: (1) spin rotation with growth and annihilation of a cross-tie structure in the stripes perpendicular to the applied field; (2) nucleation and fast motion of specific boundaries, which consist of a number of coupled vortices and antivortices located along both edges of stripes parallel to the applied field; (3) nonuniform magnetization rotation

with macrodomain nucleation and 180-degree domain wall motion in the large size unpatterned films.

It was experimentally revealed that there exists a dependence of the critical field of a nucleation and motion of boundaries in the parallel-to-field stripes on their width and frame widths. In particular, an inverse proportionality between this nucleation field and stripe width was found. For a strictly parallel orientation of the field, we have also shown the remagnetization processes are largely determined by the initial deviation of the magnetization near the stripe edges and regions where the cross connects with the peripheral frame. The kinetics and structure of the revealed boundaries are inherent to soft ferromagnetic thin films with restricted lateral size where magnetostatic fields play a main role.

References

1. Hubert, A.; Schafer, R. *Magnetic Domains*. Springer; Berlin: 2008.
2. Rave W, Hubert A. *IEEE Trans Magn*. 2000; 36:3886.
3. Cowburn RP. *J Phys D: Appl Phys*. 2000; 33:R1.
4. Barman A, et al. *J Magn Magn Mater*. 2004; 272–276:2121.
5. Bader SD. *Rev Mod Phys*. 2006; 78:1.
6. Žuti I, et al. *Rev Mod Phys*. 2004; 76:323.
7. Chappert C, Fert A, Van Dau FN. *Nature Materials*. 2007; 6:813. [PubMed: 17972936]
8. Donolato M, et al. *J Appl Phys*. 2011; 109:064511.
9. Bauer GEW. *Appl Phys Lett*. 2003; 82:3928.
10. Kleiber M, et al. *Phys Rev B*. 1998; 58:5563.
11. Li J, Rau C. *Phys Rev Lett*. 2006; 97:107201. [PubMed: 17025846]
12. Fomin LA, et al. *J Magn Magn Mater*. 2010; 322:851.
13. Fomin LA, et al. *J Magn Magn Mater*. 2013; 330:6.
14. Mironov VL, et al. *Phys Rev B*. 2010; 81:094436.
15. Takashima T, et al. *IEEE Trans Magn*. 2011; 47:2522.
16. Kim YK. *J Magn Magn Mater*. 2006; 304:79.
17. Shull RD, et al. *IEEE Trans Magn*. 2012; 48:4355.
18. Kabanov, Yu P., et al. *J Exp Theor Phys*. 2014; 118:747.
19. Shull RD, et al. *IEEE Trans Magn*. 2014; 50:2304004.
20. Mattheis R, Ramstock K, McCord J. *IEEE Trans Magn*. 1997; 33:3993.
21. Gornakov VS, et al. *J Exp Theor Phys*. 2004; 99:602.
22. Gornakov VS, et al. *Phys Rev B*. 2006; 73:184428.
23. Donahue, M.; Porter, D. OOMMF, *Object Oriented Micromagnetic Framework*. <http://math.nist.gov/oommf>

Fig. 1. Optical micrograph and macroscopic hysteresis loop of the patterned $\text{Ni}_{79}\text{Fe}_{21}$ structure.

Fig. 2. MOIF images of domain structure taken during magnetization reversal of a patterned (1A on Fig. 1) 30 μm thick NiFe film at (a) $\mu_0 H = +7.0$ mT, (b) +0.21 mT, (c) -0.24 mT, (d) -0.32 mT, (e) -0.36 mT, and (f) -7.0 mT..

Fig. 3. MOIF images of domain structure taken during magnetization reversal of the 30 μm cross (5A on Fig. 1) at (a) $\mu_0 H = +7.0$ mT, (b) $+0.7$ mT, (c) 0 mT, (d) -0.44 mT, (e) -0.5 mT, and (f) -7.0 mT.

Fig. 4. MOIF images of domain structure taken during magnetization reversal of the 10 μm cross (5B on Fig. 1) at (a) $\mu_0 H = +7.0$ mT, (b) $+0.6$ mT, (c) 0 mT, (d) -0.88 mT, (e) -0.88 mT ($+33$ ms), and (f) -7.0 mT. Inset shows an enlarged and contrasted part of the horizontal stripe. Double-arrow indicates the width d of the stripe.

Fig. 5. MOIF images of domain structure taken during magnetization reversal of the 3 μm cross (5C on Fig. 1) at (a) $\mu_0 H = -2.67$ mT, (b) -2.68 mT

Fig. 6.
Critical field $H_{\text{CR}}(b, d)$ of switching of the vertical stripes versus its inverse size.

Fig. 7. Micromagnetic simulation of the distribution of magnetization in the cross with 3 μm wide and 10 μm long arms during magnetization reversal. (a) $\mu_0 H = +5.0$ mT, (b) -5.0 mT and time t_1 , (c) -5.0 mT and time $t_2 > t_1$, (d) -10.0 mT. Inset in (c) shows in detail the $\mathbf{M}$ distribution in the horizontal stripe. The color coding of the $\mathbf{M}$ orientation is shown in (a).

Fig. 8. Micromagnetic simulation of the magnetization distribution in the framed cross with 3 μm wide and 10 μm long arms and 3 μm wide frame during magnetization reversal. (a) $\mu_0 H = +20.0$ mT, (b) -1.5 mT, (c) -2.0 mT and time t_1 , (d) -2.0 mT and time t_2 . $t_2 > t_1$.