Magnetic Ground State of Single and Coupled Permalloy Rectangles

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We have studied the magnetic domain structure in Permalloy rectangles that reveal flux-closure domain configurations. Arrays with varying spacing between the rectangles are investigated by scanning electron microscopy with polarization analysis as well as by micromagnetic simulation. In contrast to general expectation, rectangles in the flux-closure Landau state show significant coupling and form a magnetic pattern of common chirality. The coupling is due to the stray field that originates from small changes of the magnetization alignment, which is sensitive to the exact shape and the separation of the rectangles.

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One important aspect of present research on magnetism is the behavior of magnetic structures fabricated from thin films. While apparently the magnetic ground state is well known, the research is mostly dedicated to the dynamic properties after excitation either by short field or current pulses [1]. Particularly, the magnetic ground state in rectangles (1 μm $\times$ 2 μm) of ~20 nm thick Permalloy (Py) has settled as best known structure in the research on micromagnetism in general. The reason for this situation is the fact that thin rectangles are commonly accepted as paradigmatic structure that causes flux-closure domain structure in soft magnetic materials. This concept was reaffirmed when the so-called standard problems [2] were launched in the 1990s to compare the quality and accuracy of micromagnetic simulations. A rectangle with the above dimensions and magnetic parameters to mimic Py was defined as standard problem 1 (SP1). Nowadays, micromagnetic simulations are widely used and generally accepted when domain configurations are studied. In the case of SP 1, it appears to be granted that one of the two prominent flux-closure domain structures, i.e., either the Landau state [Fig. 1(b)] or the diamond state [Fig. 1(c)] is the ground state. Around 20 nm thickness these two states are close in energy [3,4] and small variations of magnetic parameters favor the one or the other. From the experimental point of view, the finding of such a state is taken as a proof for good structuring and magnetic quality. Nobody has ever proven with adequate experimental accuracy the magnetic fine structure of actual fabricated rectangles. As these structures deviate more or less from an idealized geometry, discrepancies between experimental findings and simulations made for perfect structures have to be expected. We show that the Landau structure shows significant deviations of the magnetization orientation from the four commonly assumed predominant magnetization directions. We find that a critical parameter is the exact shape of the rectangle. Since artificially created particles always have small deviations from the ideal shape, like inclined edges or edge roughness [5], the finding is of general importance, particularly when the magnetic behavior of rectangles, e.g., in external fields, is modeled.

The coupling between nano- or microstructures is another important issue in present research, as coupling has to be considered to understand the magnetization reversal behavior in arrays of nanostructures as, for example, in magnetic random access memory (MRAM) devices [6,7]. The general hypothesis is that the coupling will be important in case the single structures create a stray field, although some correlated chirality in vortex structures has been found recently [8–10]. From considerations about the stray field, it is concluded that the effects will show up for small particles [11] or in special geometries where particles with extremely elongated shape are placed head to head with very close spacing [9,12]. In the first case the particle will have a S or C state [Figs. 1(d) and 1(e)], while

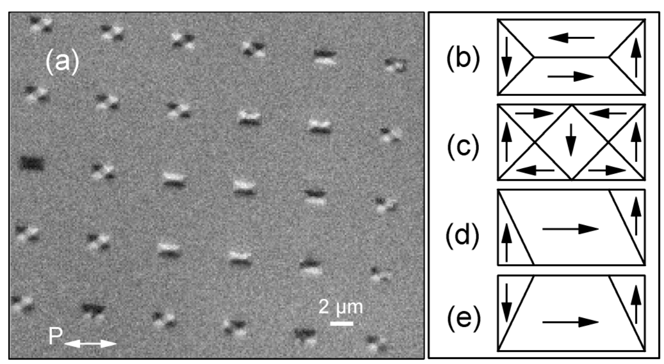

FIG. 1. SEMPA image of an array of well separated Permalloy rectangles (a). The image exhibits the magnetic structure obtained by one polarization component. The polarization sensitive axis is parallel to the horizontal edge. The dimensions of the rectangles are 1 μm $\times$ 2 μm $\times$ 23 nm. The rectangles show either the Landau state or the diamond state, only one structure is in the S state. (b)–(e) Sketch of the Landau state (b), diamond state (c), S state (d), and C state (e). "S state" and "C state" refer to the flux lines through the rectangle having shapes similar to the letters S and C, respectively.

in the latter arrangement the interaction between the charged edges of two structures is stronger than the magnetostatic interaction throughout the ferromagnet. In the case that the ferromagnetic structures create flux-closure domains to minimize the stray field energy, the coupling is assumed to be less pronounced and particularly in the low field range the coupling is believed to be of minor importance for the reversal process. These suppositions are again founded on the unrealistically idealized structure morphology. We show in this Letter that the coupling is important even in the case where the single element exhibits apparently a flux-closure structure. We first present the magnetic fine structure of Permalloy rectangles with dimensions of SP1, and switch over in the second part to the influence of coupling between closely spaced rectangles and its consequences for the micromagnetic fine structure.

The rectangles are grown via the nanostencil technique [13] by *e*-beam evaporation. The mask, a FIB structured 100 nm thick silicon nitride membrane, was brought in direct contact with the Si substrate to minimize blurring of the structure edges. The structures presented here show some edge broadening, i.e., the side faces have an angle of approximately 30° to the film plane (instead of 90° for a perfect particle), as checked by scanning electron microscope (SEM) and atomic force microscope (AFM) measurements [Fig. 2(c)]. The edge roughness was found to be smaller than 20 nm peak to peak, which corresponds to the grain size. The rectangles have lateral dimensions that match the SP1 and a slightly higher thickness of 23 nm. We have performed spatially high resolving investigations of the Py rectangles via scanning electron microscopy with polarization analysis (SEMPA). Magnetic field cycles parallel to the long axis direction of the rectangles have been applied prior to imaging. Because of the high sensitivity of our SEMPA [14] we are able to analyze very accurately the spatial magnetization orientation with an angular resolution of less than 4°. Hard axis magneto-optic Kerr effect measurements of the extended film confirm a negligible uniaxial anisotropy (~200 J/m^3).

A SEMPA micrograph of an array of uncoupled structures is shown in Fig. 1(a). Within the fraction of the array imaged, mostly Landau and diamond structures appear, while one rectangle is in the S state. A statistical investigation of the whole array (100 rectangles) reveals that Landau and diamond structures appear with equal probability (~50%). Next we focus on the details of the magnetic domain structure of the two different states [Figs. 2(a) and 2(b)]. The two SEMPA images are taken simultaneously and show the distribution of magnetization components in two perpendicular in-plane directions. The frequency distribution of magnetization orientation versus angle for the two structures is shown in Fig. 3. For the diamond state we find four accumulation peaks, which represent the magnetization of four different domain orientations appearing in the domain structure. The four magnetization directions are parallel to the edges of the rectangle, in exact agreement with general belief. The

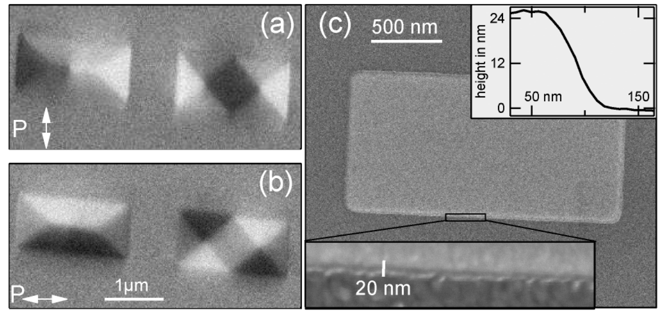

FIG. 2. Magnetic structure of Permalloy rectangles obtained by SEMPA. (a) and (b) give the images obtained via the two polarization sensitive axes oriented perpendicular to each other, parallel to the edges of the images. Both images have been measured simultaneously. (c) SEM image of a single Permalloy structure. In the lower left corner, a zoom into one edge is plotted. The inset displays an AFM line profile of the edge of the structure, which was capped by 2 nm Pt.

situation is completely different in case of the Landau state, where we find six maxima. The plot reveals that the peaks that correspond to the orientation of the long axis domain magnetization split. In the direction parallel to the long edges we do not find a single maximum in the distribution, but a splitting into two closely spaced maxima. In other words, in the Landau structure the magnetization in the larger domains is no longer aligned parallel to the long edges. The majority of the magnetization is slightly (~17.5°) turned up- or downward within the plane of the rectangle. The diamond state, on the other hand, shows a broadening of the distribution of the same magnetization orientation, which is an indication for contributions from continuously rotating magnetization.

As the splitting of the magnetization for the Landau structure was unexpected, we have performed micromagnetic simulations [15]. The geometric and magnetic parameters are taken from SP1 [2]; the simulation cell size was $(5\ \mathrm{nm})^3$, i.e., $400 \times 200 \times 4$ cells. To attain the Landau structure we relaxed the system, starting from a vortex state. The resultant frequency of magnetization orientation versus angle is plotted in black in Fig. 4. Surprisingly, the simulation shows a splitting of the long edge domain magnetization orientation as well. Such a splitting has not been discussed so far in the literature. Although hints can be found in published domain structures obtained by micromagnetic simulations [3,4,16,17], it was not further investigated as, at most, a small spreading (of no relevance) of the magnetization orientation due to a continuous magnetization rotation around the singularity was expected. Comparing our experimental result with the simulation, it is evident that the splitting angle in the experiment (35°) is larger than in the simulation (15°). To learn about the origin of this discrepancy, we have made cross-checks by varying the magnetic properties in the simulation. First we checked the influence of the magneto-

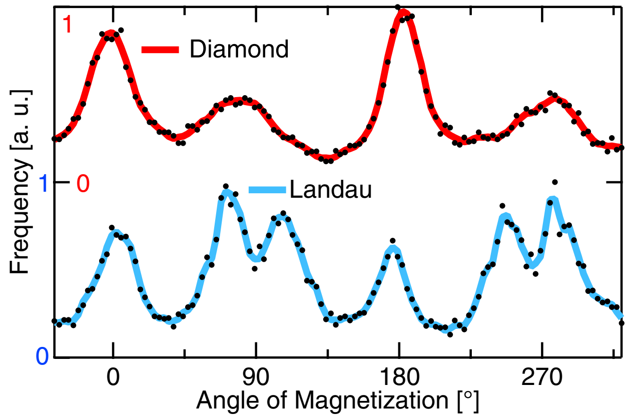

FIG. 3 (color online). Frequency of magnetization orientation as a function of angle. The angle is given with respect to the short edge of the Permalloy rectangle. The experimental data for the diamond- and the Landau structure is shown.

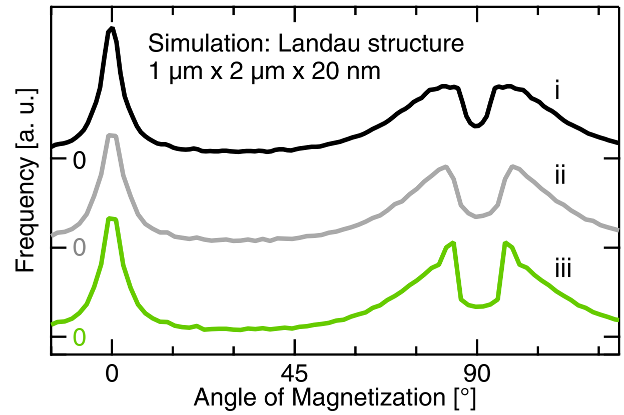

FIG. 4 (color online). Frequency of magnetization orientation as a function of angle for a single Landau structure obtained by simulations [15]. The black curve (i) gives the result for a perfect rectangle with SP1 parameters [2]. The gray plot (ii) additionaly includes edge roughness with a period of 30 nm and a peak-to-peak amplitude of 20 nm. The green curve (iii) gives the result for SP1 including inclined edges with an inclination length of 35 nm.

crystalline anisotropy. Changing the anisotropy from $+500\ \mathrm{J/m^3}$ (SP1) to $-500\ \mathrm{J/m^3}$ does not have any significant influence on the splitting angle. The only variation that showed effects was a change of the morphology of the rectangle. As the fabrication process in general generates rough and inclined edges, we have made simulations to investigate these effects: Based on our experimental findings, we have included edge roughness of a periodicity of 30 nm and a peak-to-peak amplitude of 20 nm and also modeled the edge inclination via stepwise reduction of the thickness over 35 nm. The results of the simulations are plotted as curves (ii) and (iii) in Fig. 4. Notably, the former small splitting becomes larger and more emphasized in both cases. This indicates that edge morphology is a very sensitive parameter that influences the orientation of magnetization. The splitting further increases by mutual amplification. The explanation is straightforward: volume charges are created by the 180°-Néel wall along the center, which cause a locally varying field that stipulates a locally varying magnetization. The torque on the magnetization by the volume charge is counterbalanced by the magnetic poles that will be created at the borderline of the rectangle due to magnetization in-plane tilting. As this magnetic pole density is reduced at rough and inclined edges, the demagnetizing field is smaller than that of a sharp edge [18] and the edge influence is reduced. The in-plane tilting of magnetization due to the volume charges originating from the 180°-Néel wall becomes larger with increasing edge roughness and inclination. Hence, a splitting of the long edge magnetization orientation will be always present, while the splitting angle is a measure for the edge structure. To strengthen that point, the results represented in Fig. 3 are those for the best structures we could fabricate via mask techniques. While for the idealized geometry the peaks in the angular distribution are fairly broad, indicating a gradual rotation, the peaks of the more realistic simulation are much sharper and can thus be seen as footprint of two separate domains.

Next we want to address the coupling of closely spaced rectangles. Figure 5 displays the magnetic structure of arrays of coupled rectangles obtained via SEMPA. The rectangles are arranged in a row with small spacing between the structures (nominal separation 200 nm) to render coupling across the long edges possible. The magnetization distribution of a single rectangle out of the array is shown in Fig. 6(a). The frequency of magnetization orientation taken from the same element is shown in Fig. 6(b). The histogram shows six clearly separated accumulation peaks, which are sharper than those in case of single rectangles. The splitting of the magnetization of the long axis domains is larger (46°) than for the noncoupled elements (35°). The microstructure in the former long axis domain has split up into two well-separated magnetic domains. The splitting is enhanced, which is caused by the magnetostatic interaction of the rectangles. The areas below the different peaks reveal that the size of the two new domains is comparable to that of the domains with magnetization orientation up and down [Fig. 6(a)]. In the SEMPA image the four regions can easily be identified as connected areas, i.e., domains. They are pairwise separated by a small angle Néel wall that runs perpendicular to the long edge through the line of vortices. Such a domainlike structure is known as a detail of the complex cross-tie wall [19,20].

All rectangles in the array exhibit the Landau state. All structures in a row of coupled rectangles show an identical magnetic pattern and have the same chirality of magnetization. Moreover, the vortices of the different rectangles are all perfectly aligned. Apparently, the interplay of long

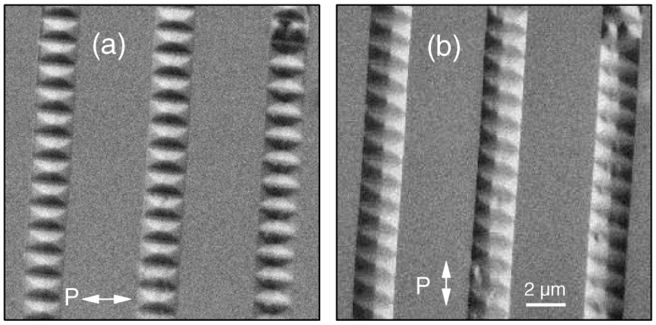

FIG. 5. SEMPA micrograph of an array of coupled Permalloy rectangles. (a) and (b) give the two polarization sensitive axes oriented perpendicular to each other, as indicated by the arrows. Both images have been measured simultaneously.

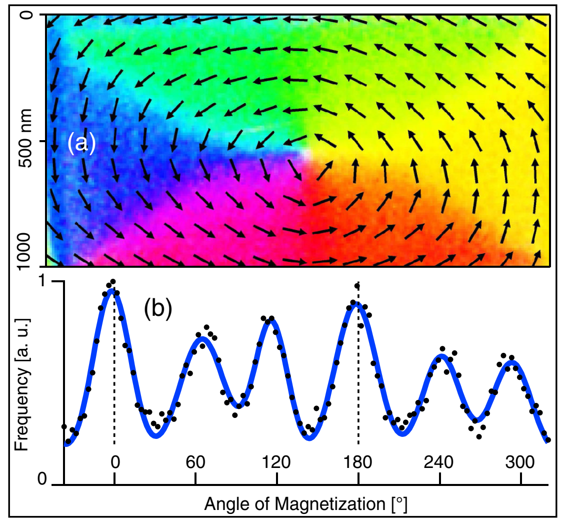

FIG. 6 (color online). Magnetization orientation of one single element from the array of Fig. 5. (a) shows a color (arrow) plot of the magnetic microstructure. The magnetization orientation was calculated from the SEMPA images. For easier understanding, arrows are given which show the direction of magnetization. (b) is the frequency of magnetization versus angle for the element shown in (a).

and short range interactions generate a new mesoscopic magnetic pattern that is originating in the instability of the single structure against in-plane tilting of the long axis magnetization orientation. The driving force is the magnetostatic interaction between the closely spaced edges that supports the creation of opposite poles. As the single-element Landau configuration is susceptive to magnetization rotation of the long edge domains, the magnetization is tilted in opposite directions in the closely spaced domains. The adjacent edges of two neighboring structures are oppositely charged. As a result all the elements are fixed regarding their microstructure and a mesoscopic structure is created throughout the whole assembly of coupled elements. The resultant structure is similar to a cross-tie wall. Typical elements of a cross-tie wall are the vortex and antivortex structures. In the coupled structures the vortices are located within the rectangles while the antivortex structures are suppressed by moving their position into the region between the rectangles. The cross-tie wall-like structure eliminates large angle domain walls in the elements and thus represents a minimum of the total energy.

In summary, we conclude that the domain structure, even in seemingly well-understood systems like Py rectangles, reveals new and surprisingly relevant details when analyzed with appropriate sensitivity. In the Landau configuration we find a splitting of the magnetization orientation of the large domains. The splitting angle increases with decreasing quality of the edges. Inevitably rough and inclined edges in experiments have a strong impact on the magnetic behavior and have to be incorporated in simulations, particularly when the behavior in external fields is considered. The susceptibility to fields is demonstrated by study of the coupling in an array of rectangles. In contradiction to common belief, the magnetostatic coupling of closely spaced rectangles with flux-closure structure is strong. The instability of the magnetization orientation of the Landau structure puts the coupling on an entirely new basis, resulting in a new mesoscopic superstructure to minimize the total energy of the whole assembly of rectangles.

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