Interaction-induced anisotropy in the onion-to-vortex transition in dense ferromagnetic nano-ring arrays

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(Received 28 September 2012; accepted 9 October 2012; published online 19 November 2012)

We show that the onion-to-vortex switching field in dense arrays of nanostructured ferromagnetic rings is strongly dependent on the angle between the applied magnetic field and the array’s main axis. The variations in switching field of up to 8 mT are connected to the anisotropy produced by dipolar interactions between domain walls in the rings. The interactions stabilize the onion state in aligned arrays but assist domain wall rotation and onion-to-vortex switching in rotated arrays. These results are established using magneto optical Kerr effect measurements of major and minor hysteresis loops together with micromagnetic simulations. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4765649]

I. INTRODUCTION

Nano sized ferromagnetic elements are attracting considerable attention due to numerous potential applications such as high density memory devices and sensors. They are also of interest because domain wall physics plays a large role on that scale. Out of the various shapes under study, ferromagnetic rings are of special importance due to their transition from a dipole-like state (also known as “onion” state), to a stable vortex state close to remanence. The magnetic vortex configuration is useful for studies of dense arrays and creating reproducible switching fields, since it introduces almost no stray field and is insensitive to element edge roughness.1 The majority of the research on ferromagnetic rings in the past decade has focused on the effect of the ring geometry on the magnetic properties. These studies produced phase diagrams for possible stable configurations,2,3 switching processes and fields,4,5 and domain wall shapes.6

However, the magnetic properties of the arrays may also be strongly affected by the interactions between the individual elements. Strong interactions between elements, such as those caused by the dipolar interaction, may result in irreproducible switching. These interactions are strongly dependent on the edge to edge distance between elements. Although this was studied in 1- and 2-dimensional arrays,7–10 very little, if any, attention was paid to the orientation of the ring array relative to the external magnetic field. While the hysteresis loop of a single ring is expected to be rotationally invariant, the array geometry may not be.11

Here, we study the effect of the array orientation relative to the applied magnetic field on the onion-to-vortex switching process. We show experimentally that magnetic interactions between rings add a strong angle-dependent effect that can hinder or assist the switching process, and change the applied field needed for its initiation. This effect should be taken into account when considering different applications for dense ferromagnetic arrays.

II. METHODOLOGY

The experiments were conducted using four different square arrays of 20 nm thick Permalloy rings. Samples were fabricated on Si substrates using electron beam lithography and evaporation. The first array, array (i), consists of rings with an outer radius of 290 nm, an inner radius of 120 nm, and array periodicity of 660 nm. The other three arrays, (ii)-(iv), consist of rings with an outer radius of 310 nm, inner radius of 100 nm, and array periodicities of 660 nm, 930 nm, and 1860 nm. Electron microscopy of the arrays and their dimensions is presented in Fig. 1.

We measured major and minor magnetization hysteresis curves of the array using the magneto optical Kerr effect (MOKE), with a focused laser spot illuminating the entire array. The external magnetic field \( \vec{H} \) is applied using a dipole electromagnet in the plane of the sample and in the reflection plane, to measure the longitudinal magnetization component (i.e., the component along the \( \vec{H} \) direction) irrespective of the array orientation. Since it is not possible to obtain the absolute magnetization from MOKE, the reverse and forward saturation magnetizations are used in each measurement for normalization purposes. During the experiment, the angle \( \theta_a \) between the array axis and the external field \( \vec{H} \) can be varied with a rotating stage as shown in the inset of Fig. 1.

III. EXPERIMENTAL RESULTS

Major hysteresis loops measured with array (i) for three different angles \( \theta_a \) are presented in Fig. 2. In each measurement, the external magnetic field is increased from an initial negative saturation of –75 mT to a positive one of 75 mT, and then decreased. The MOKE signal is measured with 1 mT intervals. All curves exhibit onion-to-vortex transitions at \( H \gg 0 - 8 \) mT, and vortex-to-onion transitions at \( H \gg 38 - 40 \) mT. The transition fields, and in particular the onion-to-vortex transition field, vary with \( \theta_a \). The inset of Fig. 2 shows the onion-to-vortex transition field as a function of \( \theta_a \). This plot is obtained by averaging the transition fields...
at the two sides of the hysteresis loop measured from array (i) for $0 < \theta_a < 65^\circ$ with $\sim 5^\circ$ steps. The onion-to-vortex transition field is defined as the field at which $M_x = M_s = 0.5$.

Hysteresis curves for $\theta_a = 0^\circ, 45^\circ$, measured with arrays (ii)-(iv), are shown in Fig. 3. Array (ii) exhibits a similar anisotropy to array (i). The effect decreases in the sparser array (iii), and vanishes completely in the sparsest one (iv). Fig. 3(d) shows a hysteresis curve obtained from a micromagnetic simulation using the NMag software package. The simulated array is a $2 \times 2$ square array with the geometric parameters of array (i) and periodic boundary conditions. The anisotropy is qualitatively reproduced by the simulation. Similar results were obtained using the OOMMF package. Both micromagnetic simulators numerically solve the dynamic Landau-Lifshitz-Gilbert (LLG) equation in order to obtain the correct micromagnetic configuration. The simulations were conducted in a manner that replicates the experiment, i.e., starting from the negative saturation field, relaxing the simulation, and raising the field in small steps until reaching the positive saturation field. In this process, the solution of each step serves as the initial condition for the following one. No specific models were built.

In addition to the major hysteresis loops described above, we also measured minor hysteresis loops. A schematic plot of a minor hysteresis loop is presented in Fig. 4(a). During the experiment, the applied field is raised from the negative saturation (A), to a certain point along the onion to vortex transition (C), and is then lowered back. The different parts of the loop correspond to different processes taking place in the sample: In sections (A and B), there is no onion to vortex switching, and the magnetization change is only due to domain wall rotation or similar reversible processes in the rings. This is validated by the fact that unless point (B) is crossed, the magnetization is single valued as a function of the applied field, without hysteresis. In sections (B and C), the rings switch from the onion to the vortex state. Sections (C and D) have an almost identical slope to (A and B), which suggests that no rings switch back and only reversible processes contribute to the magnetization change. Thus, the average height of a minor loop, normalized by the highest loop (corresponding to the entire array switching to the vortex state) is a measure of the fraction of rings that switched to the vortex state as function of the applied field. Fig. 4(b) shows the minor loops measured from array (i) for $\theta_a = 0^\circ, 45^\circ$. Note that the largest minor loop only covers the lower half of a major loop, since it is used to study the onion to vortex transition. Fig. 4(c) shows the derived number of rings in vortex state versus the applied field.
dipolar interaction. On the other hand, in Fig. 5(c), the domain walls move towards each other and annihilate. Snapshots of the simulation of this process are depicted in Fig. 5(a). We propose that when the domain walls are aligned with the applied field direction, (ii) one of the walls moves toward the other; (iii) the domain walls annihilate each other; (iv) a vortex state forms. (b) A snapshot from a simulation of an array with \( \theta_a = 0^\circ \), just before the first ring switches. The domain walls align with each other along the axis of the applied field, and thus hinder the onion-to-vortex transition. (c) A snapshot from a simulation of an array with \( \theta_a = 45^\circ \), just before the first ring switches. In this case, the domain walls are rotated away from the axis of the applied field, to align with their near neighbors.

This serves to establish the dipolar origin of the anisotropy. Alternative causes for the anisotropy, such as crystalline anisotropy or mechanical stress, can be ruled out since they would not exhibit such a dependence on the periodicity. In addition, this mechanism is consistent with the sharp notch around \( \theta_a = 45^\circ \) in the angular dependence of the onion-to-vortex transition presented in the inset of Fig. 2. At this angle, there is a high probability that the two domain walls will align along orthogonal array axes prior to switching, as in the case of the bottom ring of Fig. 5(c). Such an alignment assists the switching process by significantly decreasing the separation between domain walls.

Further support of the hypothesis that the switching process is affected by the dipolar interactions is obtained from a detailed analysis of the minor and major hysteresis loops. Our analysis allows separation of the onion-to-vortex transition from other processes that contribute to the total magnetization change. The observed magnetization change can be described as follows:

\[
\Delta M_s(H, \theta_a) = n_a \times f_o(H, \theta_a) + n_v \times f_v(H, \theta_a).
\]  

Here, \( \Delta M_s \) denotes the total change of the magnetization, as measured in a major loop experiment, \( n_a(\upsilon) \) denotes the fraction of rings in the onion (vortex) state, as derived from the minor loops experiment, and \( f_o(\upsilon) \) is the response function of a single onion (vortex) ring to the magnetic field. Since the onion-to-vortex transition occurs in a narrow field range in the vicinity of \( H = 0 \), a linear behavior of \( f_o(\upsilon) \) is assumed

\[
f(H, \theta_a) \cong a(\theta_a)H + b(\theta_a).
\]  

When Eq. (2) is substituted into Eq. (1) the equation becomes
The results show a significant difference between the behavior of a single ring in the aligned and rotated arrays below the onion-to-vortex transition. First and foremost, the ratio of magnetization slopes between the rotated 45° and aligned 0° states is very different between the onion and vortex states $a_o(45°)/a_o(0°) = 3.125$. This is shown in Fig. 3(a) where the rotated array has an early but slow increase in magnetization as the domains walls move inside the ring and approach the vortex state. The behavior is contrasted with the unrotated array, where there is practically no magnetization change due to the dipolar pinning until the transition point is reached. At that point, there is a very sharp change in the magnetization as the onion changes to the vortex state. The attribution of this effect to the domain wall movement requires dense ferromagnetic ring arrays.

The $b_{o/v}$ fitting coefficients give information about the remanent configurations of the rings. Rings in the vortex state have perfect polar symmetry, and when the anisotropic effect of the external field is removed, there should be no difference whatsoever between the vortex configurations in aligned and rotated arrays. Indeed in the vortex state $b_v(45°) = b_v(0°)$. This proves that the angular anisotropy is introduced either by the external field or by the array, through the domain wall coupling. When both mechanisms are removed complete angular isotropy is restored.

If the domain walls in the onion state were perfect dipoles, all aligned along the array axes at remanence, one would expect the ratio $b_v(45°)/b_v(0°)$ to be $\sin(45°) = 1/\sqrt{2}$. The actual measured ratio is $b_v(45°)/b_v(0°) = 0.87$, which indicates an effective rotation of $\sim 30°$. The slightly smaller than expected effective rotation can be attributed to partial rotation of the onion state in some of the rings, or of the individual domain walls as in Fig. 5 (a-iii). The $\sin(45°)$ ratio is probably the theoretical upper limit.

V. SUMMARY

In summary, we found an angular anisotropy in the onion-to-vortex transition in dense ferromagnetic ring arrays with up to 8 mT changes in the switching field as a function of array orientation. The data imply that this anisotropy arises from dipolar interactions between domain walls of adjacent rings in the onion state. We show that in arrays aligned with the external field, the interaction stabilizes the walls and thus sharpens the switching process. On the other hand, in rotated arrays the nearest neighbor domain walls assist domain wall rotation thereby also assisting the switching process ultimately making the transition wider. The phenomenon is also qualitatively reproduced in numerical micromagnetic simulations. This effect should be a significant consideration in the design of any application that requires dense ferromagnetic ring arrays.

ACKNOWLEDGMENTS

We would like to thank Siming Wang for useful discussions. This work was supported by the US AFOSR under Grant No. FA9550-10-1-0409.

TABLE I. Fitting results.

<table>
<thead>
<tr>
<th>$a_o$</th>
<th>$a_v$</th>
<th>$b_o$</th>
<th>$b_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>0.015 ± 0.002</td>
<td>0.0047 ± 0.0003</td>
<td>−0.74 ± 0.02</td>
</tr>
<tr>
<td>0°</td>
<td>0.0048 ± 0.00</td>
<td>0.0052 ± 0.0005</td>
<td>−0.85 ± 0.01</td>
</tr>
</tbody>
</table>

$\Delta M_s(H) = n_o(a_oH + b_o) + n_v(a_vH + b_v)$,