Magnetization states in coupled Ni$_{80}$Fe$_{20}$ bi-ring nanostructures

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Abstract. The effects of magnetostatic and exchange coupling between two circular Ni$_{80}$Fe$_{20}$ rings on the magnetization reversal process and spin configuration are investigated using focused magneto-optic Kerr measurements and magnetic force microscopy measurements. When the two rings are contiguous and exchange coupled, the reversal occurs via a three-stage process leading to a significant reduction of the vortex–onion switching fields when compared to magnetostatically coupled ring pairs or isolated rings of the same lateral dimensions. For exchange-coupled rings, the chirality of the vortices in the two rings is correlated. The experimental results are compared to micromagnetic simulations.

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1. **Introduction**

Submicron ferromagnetic ring-shaped structures may be useful in magnetic random access memory (MRAM) and magnetic sensors [1, 2]. For a single-layer ferromagnetic ring in an in-plane field, two characteristic magnetic states are observed [3]: the onion state, containing two 180° walls, and the flux-closed vortex state without walls. The nucleation and annihilation fields of the vortex and onion states have been extensively studied in isolated nanorings [4]–[8]. However, when the inter-ring spacing is less than the ring diameter, magnetostatic interactions become important in determining the magnetic states of the patterned structures [9, 10]. Bringing two rings into physical contact leads to exchange coupling between the rings, which significantly affects the magnetization reversal process. This has been shown previously in overlapping thin film dots [11]–[18]. Welp et al [11] investigated the magnetization reversal behavior for an array of connected rings and observed that the coupling among the rings introduces a broad distribution of switching fields. Rose et al [12] also investigated the magnetization behavior of connected rings arranged in a tri-ring structure, which led to a magnetically frustrated state. Further, Arrott [15] investigated theoretically the magnetic states of a hysteron consisting of overlapping circles, and observed that reversal does not necessarily require domain wall nucleation, resulting in low switching fields. In ferromagnetic rings, limited work has been reported on how exchange coupling between two neighboring rings affects the magnetization reversal process.

In this paper, we describe how the coupling between two rings affects their magnetic state. We fabricated four different arrays of ferromagnetic bi-rings, consisting of overlapping, connected, closely packed and isolated rings. The overlapping and connected structures consisted of a pair of rings in physical contact, while the closely spaced and isolated bi-rings consisted of a pair of separated rings. The closely spaced and isolated bi-rings displayed double-step switching resulting from the onion-to-vortex and vortex-to-reverse onion state transitions, similar to an individual ring. However, the overlapping and connected samples showed a more complex three-step reversal with a strong angular dependence.

2. **Experimental methods**

Periodic arrays of widely spaced Ni$_{80}$Fe$_{20}$ bi-ring structures separated by 1.2 μm were fabricated using electron-beam (e-beam) lithography followed by e-beam evaporation and lift-off processes. A Ni$_{80}$Fe$_{20}$ layer of thickness 50 nm was deposited using e-beam evaporation at a
Figure 1. Scanning electron micrographs (SEMs) of the Ni$_{80}$Fe$_{20}$ bi-ring structures.

The magnetic switching behavior of the bi-rings was characterized at room temperature by focused magneto-optical Kerr effect (MOKE) magnetometry with a spot size of about 5 $\mu$m, so that 2–4 bi-rings were imaged simultaneously. The magnetic states of the patterned structures were characterized by magnetic force microscopy (MFM) with a low-moment CoCr tip at a constant scan height of 80 nm. Understanding the reversal mechanism in the nanomagnets is facilitated by micromagnetic modeling, which was performed using NIST’s 3D OOMMF code [19]. The bi-rings were discretized into 10 nm $\times$ 10 nm $\times$ 10 nm cells in the x, y and z directions, so that each bi-ring was made up of five layers of cells. The five layers showed very similar magnetic states, and data from the middle layer are reported in this paper. The contact length in the simulated connected bi-rings was 150 nm. The intrinsic anisotropy of the Ni$_{80}$Fe$_{20}$ film was neglected. Standard parameters were used for the properties of Ni$_{80}$Fe$_{20}$, i.e. exchange constant $A = 13 \times 10^{-12}$ J m$^{-1}$, saturation moment $M_s = 860 \times 10^3$ A m$^{-1}$ and vacuum permeability $\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$, giving an exchange length of $L_0 = \sqrt{2A/\mu_0(M_s)^2} = 5.3$ nm and anisotropy $K_1 = 0$.

3. Results and discussion

3.1. Field applied along the long axis of the bi-rings

Figure 2(a) shows the M–H loops of the Ni$_{80}$Fe$_{20}$ bi-rings for an in-plane magnetic field applied along $\theta = 0^\circ$, the long axis of the bi-rings. The corresponding switching fields are determined from the derivative of the M–H loops shown in figure 2(a). For the overlapping bi-rings, the...
Figure 2. (a) MOKE M–H loops for the four bi-ring configurations for a field applied along $\theta = 0^\circ$. The lower panel gives the derivative of the M–H loop for the overlapping bi-rings. (b) The corresponding simulated M–H loops. The simulated magnetic configurations for overlapping (left) and connected (right) bi-rings are shown in the inset of (b). (c) MOKE M–H loops at $\theta = 90^\circ$ for the four samples.

M–H loop shows a distinct three-step switching with the three switching fields $H_{s1} = -55$ Oe, $H_{s2} = -227$ Oe and $H_{s3} = -309$ Oe. The connected bi-rings also display three switching steps with switching fields $H_{s1} = -57$ Oe, $H_{s2} = -334$ Oe and $H_{s3} = -413$ Oe, although the step at $H_{s2}$ is indistinct. For the closely spaced and isolated bi-rings with $s = 50$ and 500 nm, two-step switching is seen, attributed to the onion-to-vortex ($H_{s1} = -60$ and $-52$ Oe, respectively) and vortex-to-reverse onion ($H_{s2} = -510$ and $-508$ Oe) transitions occurring in each ring.
The differences in switching behavior can be related to the type of coupling within the bi-rings. For the overlapping and connected bi-ring, the strong exchange coupling dominates the magnetization reversal mechanism. For closely spaced bi-rings with \( s = 50 \text{ nm} \), dipolar coupling dominates the reversal process. For the isolated bi-rings with \( s = 500 \text{ nm} \), where magnetostatic coupling is weaker, the loop resembles that of the closely spaced bi-rings, with slightly lower switching fields.

Three-dimensional micromagnetic simulations were performed for the four types of bi-rings, shown in figure 2(b). All simulated M–H loops show a two-step switching, representing onion–vortex and vortex–reverse onion transitions. For the closely spaced and isolated bi-rings, the onion and vortex states are the same as those seen in a single ring. However, for the overlapping and connected bi-rings, these states differ from those of a single ring. The onion (high remanence) and vortex (low remanence) states of overlapping and connected bi-rings are shown in the insets of figure 2(b). The onion states for both geometries are similar, and include two domain walls along the field direction at the opposite outermost edges of the bi-ring, with an additional domain wall in the overlapping area. However, the vortex states differ. The simulations show that the overlapping bi-rings form a vortex state in which each ring has the same chirality with a domain wall present in the overlapping region. However, connected bi-rings form a vortex state in which the two rings have opposite chirality, and there is no domain wall at the region where the rings intersect.

The first step in the hysteresis loop for all the samples corresponds to the onion–vortex transition. For all the samples, this occurs by the movement of the outermost DWs, giving a similar switching field of \( \sim -50 \text{ Oe} \) for all four geometries, as seen experimentally. The second step in the simulated loops, corresponding to the vortex–reverse onion transition, shows a greater variability between the samples. The vortex–reverse onion transition in the simulation occurs at the lowest field magnitude for the overlapping rings (\(-409 \text{ Oe}\)), compared to \(-450 \text{ Oe}\) for the connected bi-ring and \(-514 \text{ Oe}\) for the isolated and the closely spaced bi-rings. The easier reversal of the overlapping bi-ring resembles the results for overlapping discs known as a ‘hysteron’ [15, 16] in which the switching field is low, because the structure can reverse without requiring domain wall nucleation.

The simulations agree well with the experimental loops, with the exception of the intermediate step seen in the overlapping and connected bi-rings, which is not present in the simulation. The intermediate state possibly corresponds to one of the rings switching to an onion while the other remains in a vortex, or to averaging over more than one bi-ring, which would not be captured in a simulation. For the connected rings, experimentally the intermediate state is barely visible for the field along the bi-ring axis, but it becomes more distinct when the field is applied at different angles, as described below.

Based on the simulations, the exchange \( (E_{\text{ex}}) \) and magnetostatic \( (E_{\text{m}}) \) contributions to the total energy of the bi-rings are shown in figures 3(a) and (b) as a function of the external applied field, for overlapped, connected and closely spaced bi-rings. The magnetostatic term is dominant. In the onion state, as the applied external field is reduced towards zero, the exchange energy increases as the domain structure develops, while the magnetostatic energy decreases. As the rings transition to the vortex state, the exchange and magnetostatic terms decrease sharply. An increase occurs at the vortex–reverse onion transition. In the vortex regime, \( E_{\text{m}} \) is similar for the three bi-ring geometries, but \( E_{\text{ex}} \) differs as a result of the contribution of the domain structure that forms at the intersection of the rings: \( E_{\text{ex}} \) is smallest for the closely spaced bi-ring and largest for the overlapping bi-ring. In contrast, in the onion regime, \( E_{\text{ex}} \)
Figure 3. (a) Exchange energy ($E_{ex}$) and (b) magnetostatic energy ($E_{m}$) variations as a function of external applied field for the overlapping, connected and closely spaced bi-rings. (c) The magnetostatic energy ($E_{m}$) at remanence as a function of inter-ring spacing ($s$) for two rings with an inner diameter of 600 nm and an outer diameter of 1200 nm.

is similar for the bi-rings, but $E_{m}$ differs, being largest for the closely spaced bi-rings, and smallest for the connected bi-rings.

MFM imaging of the domain configurations at remanence was used to understand the magnetic states of the bi-ring structures. The samples were first saturated at +1200 Oe and then placed in a reverse field in the range of −100 to −500 Oe before imaging. The light and dark contrast indicates the presence of magnetic charges at the positions of domain walls. Figures 4(a)–(d) show examples of MFM remanent images and micromagnetic simulations (relaxed to remanence) at $\theta = 0^\circ$ for the four samples.

For overlapping bi-rings, at $\theta = 0^\circ$, data and simulation are shown after applying reverse fields of −100, −250 and −400 Oe (figure 4(a)). The model predicts at −100 and −250 Oe the existence of a low-remanence vortex state with the same chirality in each ring, as seen in
the inset of figure 2(b). This occurs because the outermost domain walls in the bi-ring move in the same direction perpendicular to the bi-ring axis, necessarily leading to the same chirality in the two rings. At $-400 \text{ Oe}$, the overlapping bi-ring has just switched to the reverse onion state.

Experimentally, the MFM data suggest a different reversal process. At a reverse field of $-100 \text{ Oe}$, a bright–dark contrast is seen in the MFM image at the intersection region. After increasing the reverse field to $-250 \text{ Oe}$, which corresponds to the second (intermediate) plateau region in the M–H loop, the MFM shows a displacement of the contrast, perpendicular to the bi-ring axis. The presence of bright–dark contrast is similar to the contrast seen when imaging $360^\circ$ domain walls [20]. We presume that this contrast indicates that the two rings in the bi-ring actually have opposite chirality, with a metastable complex domain wall in the intersection region. Collapse of the metastable structure would yield a contrast-free state, as seen at higher field angles (described below). The formation of the opposite-chirality vortex state can occur if the two walls in the onion state are initially translated in opposite directions perpendicular to the bi-ring axis during the onion–vortex transition. At $-400 \text{ Oe}$, the sample showed a partial transformation to the reverse onion state, where the dark-contrast wall is located at one end of the bi-ring, while the bright-contrast wall is part way around the other ring.

The difference between the model and experimental data is most likely due to the greater symmetry of the model. In the experiment, the rings have edge roughness and other inhomogeneities that will likely pin one of the outermost domain walls more strongly than the other, leading to a multi-step reversal. Inhomogeneities can also stabilize metastable states such as $360^\circ$ walls, which could be eliminated in the model. The model also assumes that the field is accurately aligned with the bi-ring axis, whereas in experiments deviations are likely. Further modeling showed that both the stability range of the vortex and the chirality in the vortex state are sensitive to small deviations of e.g. $2^\circ$ in the applied field angle.
These experimental factors can all influence the formation mechanism of the vortex. The direction of movement of a domain wall around a circular ring is determined stochastically [21], as well as by asymmetries in the ring and the experimental conditions, making prediction of the vortex chirality difficult. If the walls move in opposite directions during the onion–vortex transition, the vortex state of the bi-ring will consist of two rings with opposite-chirality vortices, while if they move in the same direction, the vortex state will consist of two rings with the same chirality.

The intermediate step in the experimental hysteresis loop may represent the partial reversal of a ring by the movement of one of the domain walls before the other. It is also possible that this arises because the MOKE system averages the signal from 2–4 rings, and these may switch at different fields. The MFM did not indicate a qualitatively different magnetization configuration at −250 Oe (although there was an axial displacement of the contrast), which may favor the latter interpretation, although measurements on a single bi-ring are needed to confirm this.

For the connected rings, at a reverse field of −100 Oe, modeling suggests that the two rings are in a vortex state (figure 2(b), bottom right inset), but the chirality of the two rings is opposite, as a result of the exchange coupling along their edges [12]. Because there is no domain wall in this structure, MFM images of bi-rings cycled to −100 or −250 Oe (not shown) have no contrast. This confirms the presence of vortex states of opposite chirality in the bi-rings, although it does not indicate which ring has clockwise and which has counterclockwise chirality. No distinct contrast corresponding to the small hysteresis plateau at −400 Oe could be observed. At higher field, the onion state is formed (figure 4(b)). The MFM indicates partial reversal of the sample imaged at −450 Oe, with contrast near the intersection region.

For the closely spaced and isolated bi-rings with $s = 50$ and 500 nm, saturation and subsequent removal of the field leads to the rings being in onion states. Vortex states are formed from the onion states by the motion of one of the walls around each ring to annihilate the other wall. Because of the magnetostatic coupling between the innermost onion-state domain walls, the onion–vortex transition occurs by the motion of the outermost walls [22]. MFM (not shown) has no contrast, confirming that a reverse field of −100 Oe leads to both rings of each pair being in a vortex state, although it does not give their chirality. A higher field, e.g. −500 Oe for the isolated bi-ring, formed the onion state with the domain walls visible in the expected locations. The closely spaced bi-ring also showed contrast at −450 Oe, although the locations of the domain walls were not at the ends of the bi-ring, probably because this field is insufficient to saturate the bi-rings and only partly reversed the sample.

The similarity in behavior of the closely spaced and isolated bi-rings suggests that the reversal process is relatively insensitive to the inter-ring spacing $s$ in the range examined here, 50–500 nm. Figure 3(c) shows the magnetostatic component of the total energy calculated from the micromagnetic simulation as a function of spacing $s$ for bi-rings at remanence after saturation. The data show only a slight rise with increasing $s$ above 50 nm.

### 3.2. Angular dependence of hysteresis of the bi-rings

The measured M–H loops for $\theta = 90^\circ$ are given in figure 1(c) for the overlapping, connected, closely spaced and isolated bi-rings. Compared to $\theta = 0^\circ$, for the overlapping and connected bi-rings, reversal initiates at a lower reverse field but the second and third steps occur at a higher reverse field, particularly for the overlapping bi-rings, leading to a much wider
vortex-state plateau with near zero remanence. No significant difference between the loops measured at $\theta = 0^\circ$ and $90^\circ$ was observed for the closely spaced or isolated bi-rings.

Figure 5 shows the MOKE M–H loops as a function of field angle $\theta$ for the overlapping and connected bi-rings. The amplitude of the intermediate switching field $H_{s2}$ decreases with the field angle, and above $45^\circ$ only two-step switching was observed. Figure 5(a) shows the MFM images at remanence for $\theta = 45^\circ$ for the overlapping bi-rings and the simulated magnetic configurations. At $\theta = 45^\circ$, a reverse field of $-100$ Oe leads to vortex states without contrast, but at $-250$ Oe a displaced bright–dark contrast is visible similar to that seen at $\theta = 0^\circ$. At a reverse field of $-100$ Oe, modeling suggests that the two rings are in vortex states of opposite chirality, in agreement with the contrast-free MFM image seen. At $\theta = 90^\circ$ the contrast-free vortex is seen at both field values (not shown).

This observation suggests that experimentally, the overlapping bi-ring forms a vortex state in which the two rings have opposite chirality, with or without a metastable structure at the intersection region, for all three field angles imaged here. The model, in contrast, predicted a change from same-chirality to opposite-chirality vortex states with increasing angle. This is a consequence of the off-axis field promoting a magnetization direction parallel to the field.
the elongated intersection region, which can be seen in the simulated magnetization states in figure 5(a).

For the connected bi-rings, the magnitude of the second step compared to the third step increased with the field angle. MFM for 45° and 90° field angles in figure 5(b) shows no contrast at remanence after applying −100 Oe (not shown), which is consistent with opposite-chirality vortex states in the two rings. However, at −300 Oe, contrast is seen near the intersection region at both field angles. The origin of the contrast is unclear, but because the rings have opposite vortex chirality at −100 Oe, we assume that this is also the case at higher fields. The model actually predicted vortex states in which the rings have the same chirality. This may be partly a result of the short intersection length of the rings in the model, which leads to only a small energy contribution from the domain wall at the intersection of the rings, compared to the experimental case.

Finally, we discuss the angular dependence of the two-step switching fields $H_{s1}$ and $H_{s2}$ for the closely spaced bi-rings. The magnetostatic interaction between onion-state rings is expected to vary with field angle [23], because this changes the effective spacing between the domain walls. However, $H_{s1}$ and $H_{s2}$ show only a modest variation with field angle and exhibit average values of 50 ± 15 and 490 ± 20 Oe, respectively. This result is in contrast to the reversal behavior in circular magnetic dots [24], where the strong magnetostatic interactions between dots with 55 nm spacing induced significant configurational anisotropy in the system, which was used for manipulating the vortex chirality. The behavior was explained as a result of the interaction of the side charges present in the circular dots when a vortex core was nucleating at the edges. However, in the case of circular rings, the reversal mechanism differs. $H_{s1}$ represents the field to unpin the outermost domain walls, which has little dependence on field angle. $H_{s2}$ represents the field needed to nucleate a reverse domain in a vortex-state ring. At this state, the two rings do not interact significantly so $H_{s2}$ is expected to be field angle independent. In practice, there may be magnetostatic coupling even between vortex-state rings due to dynamic stray fields [25], leading to an angular dependence of $H_{s2}$.

4. Conclusions

We have investigated how the coupling mechanism affects the magnetic states and reversal processes in overlapping, connected, closely spaced and isolated bi-ring structures using MOKE and MFM characterization techniques. For field applied along the easy axis, the overlapping and connected exchange-coupled bi-rings display three-step switching with a significant dependence of switching fields on field angle. The bi-rings form vortex states where the vortex chirality of the two rings composing the bi-ring is correlated. MFM data suggest that the vortex chirality of the two rings is opposite for the samples examined, and support the existence of a metastable magnetization structure at the intersection region of the overlapping rings. Simulation results suggest that both same-chirality and opposite-chirality vortex states can be obtained, and we expect that this can be controlled by adjustment of the ring geometry and detected by MFM. In contrast, the magnetostatically coupled bi-rings and isolated rings exhibited a simpler two-step switching process corresponding to the onion-to-vortex and vortex-to-reverse onion transitions. Furthermore, there is no significant difference in behavior between closely spaced and isolated bi-rings. These results show that by configuring the ring elements in different arrangements, a variety of magnetization reversal behaviors can be obtained.
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