Numerical studies of demagnetizing effects in triangular ring arrays

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We study the effect of the magnetostatic field in a two-dimensional periodic square array of Permalloy triangular rings by means of micromagnetic simulations. The rings have a lateral size of 50 nm, an edge width of 8 nm and the thickness is 10 nm. Applying an external field to one of the elements and assuming the rest of the array to be in the remanent state, we show how the remanent magnetization and coercive field are affected by the magnetostatic field of the array, both as a function of the distance between the elements and as a function of the number of elements used to model the periodic array. We provide an estimate of the minimum distance for an independent behavior of the elements, and we show that a model with the first and second nearest neighbors of an element can accurately approximate the effect of a much larger array.

INTRODUCTION

A thorough understanding of magnetostatic coupling in arrays of magnetic nanostructures is essential for high-density magnetic recording applications. Large areal densities are achieved reducing the distance between the array elements, but magnetostatic effects could undermine their independent behavior.

A promising solution to reduce this problem is the use of ring-shaped elements [1], where the closure-like natural magnetic configurations avoid the formation of strong stray fields. Imperfections in the manufacturing process can break the reversal symmetry and degrade the magnetic properties of circular rings [2], whereas in triangular rings the presence of the corners, which act as pinning centers for the magnetization, allow to have an high control on the possible magnetic patterns [3].

The properties of isolated triangular rings have been reported in a number of publications (*e.g.* [2–6]). In this paper we consider an array of interacting triangular rings and present a numerical investigation of their magnetostatic interactions as a function of the spacing between the elements and the number of elements used in the array.

COMPUTATIONAL MODEL

To study the magnetostatic interactions in arrays of magnetic elements a common approach is to consider one element of the array, to take the remanent magnetization and coercive field as the characterization parameters, and then to analyze how these parameters are affected by the demagnetizing field produced by the rest of the array [7, 8].

As shown in Fig. 1, the array is made of a square lattice of triangular rings and we use the same periodicity p for the x and y directions. The size of the array varies between 3×3 and 11×11 rings with a periodicity p
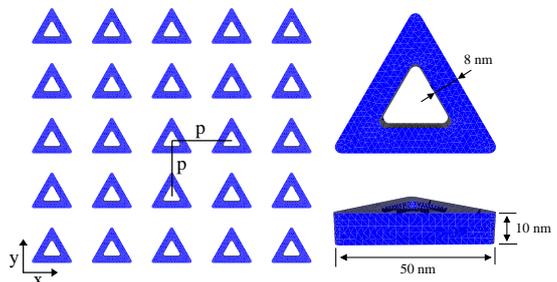

FIG. 1: Geometric characteristics of a 5×5 array with periodicity p. The applied field is directed roughly along the x-axis, tilted by $\sim 5.7°$ in the x-y and x-z planes.

between 53 nm and 150 nm. Each ring is an equilateral triangle with a lateral size of 50 nm, edge width of 8 nm and a thickness of 10 nm. For the material, we use the standard parameters of Permalloy: exchange coupling constant $A = 1.3 \cdot 10^{-12}$ J/m, saturation magnetization $M_S = 860 \cdot 10^3$ A/m and zero magnetocrystalline anisotropy. The external field is applied in-plane roughly along the x-axis, tilted off by 0.1 radians ($\sim 5.7°$) in the x-y and x-z planes to avoid possible numerical artifacts in the magnetic configurations assumed by the system.

For our simulations we use the *Nmag* micromagnetic simulation software [9]. With reference to Fig. 1, we call $N_r = 5$ the number of rows of the square lattice and we study the behavior of the central triangular ring under the influence of the $(N_r^2 - 1) = 24$ other triangular rings and an applied field. The magnetization of the 24 outer rings is kept fixed during the whole simulation.

We have obtained this fixed magnetization for the outer rings by computing the equilibrium configuration of a quasi-periodic $N_r \times N_r$ array of triangular rings with an initial magnetization pointing uniformly in the x-direction. In essence, this computational method [10] enforces that the magnetization is identical in all N_r^2 rings, while taking into account the full (non-periodic) demagnetizing field that emerges from all N_r^2 rings.
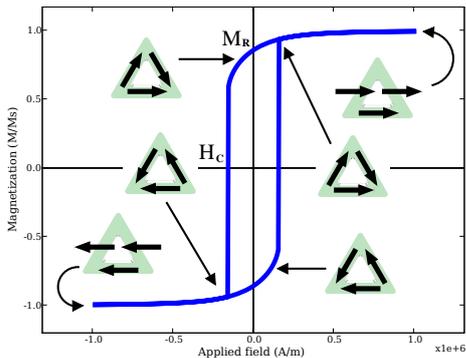
FIG. 2: Hysteresis loop of an isolated ring. The magnetic configurations at saturation, remanence and coercivity are shown in Fig. 3.

FIG. 3: Bending angle α of the magnetization at the lateral corners L and R going from the saturation configuration (I) to the remanence (II) and the coercive field (III) in Fig. 2. The reversal is driven by the magnetization in the top corner T, where the out-of-plane component is largest.

FIG. 4: Coercive field and remanent magnetization as a function of the array periodicity. The values for an isolated ring are those with $p = \infty$.

In more detail, this is achieved by simulating only one triangular ring, and simulating the presence of the periodic copies by adding extra contributions to the Boundary Element Matrix which come from magnetic surface dipoles on the displaced copies. This introduction of magnetic "mirage charges" into the FEM/BEM method [11] parallels the introduction of mirror charges in electrostatics. Using this method we can obtain the demagnetizing field of a very large array with the memory requirement of a single-ring simulation.

The remanent magnetization obtained with this procedure is virtually identical to the remanent magnetization of an isolated ring as shown in Fig. 3-II. As all rings have the same magnetization, this configuration will overestimate the demagnetizing field (because the rings do not have the freedom to react individually).

ISOLATED RING

The hysteretic behavior of an isolated ring is shown in Fig. 2. Starting from an applied field of 10^6 A/m, corresponding to the saturated magnetization distribution in Fig. 3-I, the field is decreased in steps of $5 \cdot 10^3$ A/m. At remanence (Fig. 3-II) the magnetization bends on the top corner and bottom edge to reduce the demagnetizing field from surface charges on the lateral edges. The lateral corners L and R in Fig. 3-I act as pinning centers around which the magnetization rotates. As shown in Fig. 3 the angle α of the magnetization at these corners goes from 0° at saturation, to 30° at remanence and reaches 60° right before the switching. The coercive field is $H_C = 157.5 \cdot 10^3$ A/m, corresponding to 198 mT.

The switching mechanism occurs without the intermediate vortex states found in larger rings [4]. The out-of-plane component of the magnetization is largest at the top corner of the ring. At H_C this corner acts as a nucleation region and the magnetization reverses simultaneously over all the ring.
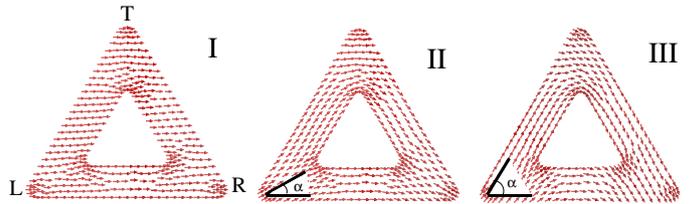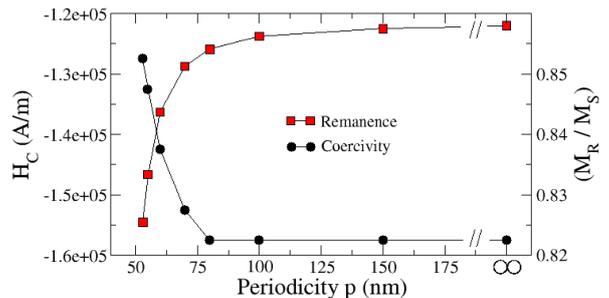
EFFECT OF PERIODICITY

To study the variation of the remanent magnetization and coercive field as a function of the periodicity p we use an array of 121 elements on a 11×11 square lattice.

We compute the hysteresis loop of the central ring in the presence of the neighbor rings as described in section II and determine the coercive field and the remanent magnetization. We use values of the periodicity p between 53 and 150 nm, corresponding to spacings between 3 and 100 nm between the rings. We find that the reversal mechanism remains the same as that of the isolated ring for all the values of p except 53 nm. In that case the reversal goes through an intermediate state where the magnetization assumes an out-of-plane configuration in the left corner of the ring.

The remanent and coercive fields as a function of periodicity are shown in Fig. 4.

The coercive field H_C of the isolated ring ($p = \infty$ in Fig. 4) is maintained for values of p of 150 nm, 100 nm and 80 nm. For smaller values of p the magnetostatic interactions affect the switching point of the ring and the magnitude of H_C decreases up to $127.5 \cdot 10^3$ A/m (corresponding to 160 mT) at periodicity $p = 53$ nm.

Concerning the remanent magnetization M_r, a deviation from the isolated ring case is present for all finite values of p. The largest difference, of about 4%, occurs at $p = 53$ nm. At $p = 80$ nm, where the deviation of H_C

from the ideal case (isolated ring) is negligible, the deviation of M_r is below 1%. Assuming that a 1% difference in H_c and M_r can be taken as a good approximations of the ideal behavior, we deduce that a spacing of 30 nm is the lower limit for an independent behavior of the rings.

REDUCED ARRAY

Carrying out the simulations of the array of rings is more demanding in required execution time in comparison to the isolated ring, while the memory requirements are the same (because we store out the BEM matrix containing the sum of the contributions from the periodic copies). This extra time effort is proportional to the number of periodic copies, and proportional to the square of the number of surface nodes in the mesh of one ring (which determines the size of the BEM matrix). In order to minimize the setup time of the simulation it is then interesting to know which is the minimum size of the array which guarantees a good approximation of the truly periodic system. To answer this question we consider the set of square arrays ranging from 3×3 to 11×11 elements, and compare their H_c and M_r. The results of this analysis are shown in Fig. 5 and 6.
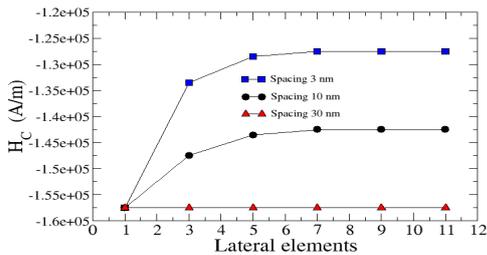

FIG. 5: Coercive field of reduced arrays as a function of the lateral size and the spacing between the elements.
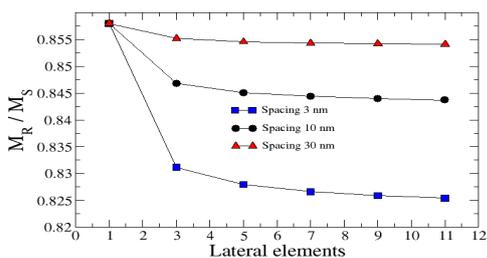

FIG. 6: Remanent magnetization of reduced arrays as a function of the lateral size and the spacing between the elements.

Reducing the number of elements of the array, the magnetic behavior for different values of p is qualitatively similar to the largest system considered (11×11 elements).

However, from a quantitative point of view, the number of lateral elements needed to reproduce the periodic behavior increases going from 30 nm to 3 nm spacing (corresponding to p ranging from 80 to 53 nm). Concerning the remanent magnetization, a 3×3 array is sufficient to create a remanent magnetization within 99% of the 11×11 value for all the spacings considered. For the coercive field an equivalent deviation is achieved with a 5×5 array. The effect from first and second nearest neighbors in a square array is therefore a good approximation of a much larger array.

SUMMARY

We investigate the effect of the demagnetizing field in a square array of 50-nm size triangular elements as a function of the spacing between the elements and as a function of the number of elements used to approximate the array. We find that 30 nm spacing between the elements is sufficient to have a deviation smaller than 1% from the behavior of an isolated ring. Our analysis also shows that 5×5 elements are sufficient to have the same effect as a much larger array, since the deviation in H_c and M_r between 5×5 and 11×11 elements is below 1%.

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