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Cobalt double-ring and double-dot structures: Magnetic properties

F. López-Urías [a,*], J.J. Torres-Heredia [b], E. Muñoz-Sandoval [a]

[a] *Advanced Materials Department, IPICYT, Camino a la presa San José 2055, Col. Lomas 4a sección, 78216, San Luis Potosí S.L.P., México*
[b] *Instituto Tecnológico Superior de Las Choapas, Col. J. M. Rosa do, 96980, Las Choapas, Veracruz, Mexico*

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ABSTRACT

The magnetization reversal mechanism of nanostructures of cobalt double-rings (D-rings) and double-dots (D-dots) is investigated in the framework of micromagnetic simulations. The arrays contain two identical coupled rings (wide and narrow) or dots with outer diameter of 200 nm and thicknesses ranging from 2–20 nm. Hysteresis loops, dipole–dipole and exchange energies are systematically calculated for the cases of the structures touching and the structures with a 50-nm inter-magnet separation; moreover, magnetization states along the hysteresis curve are analyzed. The results of both dot and ring D-magnets are compared with the corresponding individual magnets. Our results reveal that all D-ring (in contact and separated) arrays containing narrow rings exhibit non-null remanent magnetization; furthermore, higher coercive fields are promoted when the magnet thickness is increased. It is observed that the magnetization reversal is driven mainly by a clockwise rotation of onion-states, followed by states of frustrated vortices. Our results could help improve the understanding of the magnetic interactions in nanomagnet arrays.

1. Introduction

Due to the potential applications in ultra-high-density magnetic recording medium, two-dimensional arrays containing rings, particles, wires and dots have attracted much attention [1–5]. Currently, ferromagnetic arrays are fabricated with advanced lithographic techniques [6–8] and characterized by magnetic force microscopy [9,10]. The ring geometry has been found to be an excellent candidate for the magnetic random access memory because the vortex state in circular rings is stable and easy to control when they are narrow [11–23]. For example, the role of the magnetic interactions in chains formed by touching rings was experimentally investigated by Welp et al. [24]. They found that the switching occurs in a pair-wise manner when the external magnetic fields are applied in-plain and perpendicular to the chain direction. This coupling introduces a broad distribution of switching fields and corresponds to a broad magnetization loop. Thus, the switching for both the isolated and the coupled rings occurs through the formation of a buckled state and the nucleation and propagation of a vortex domain wall. Adeyeye et al. [25] also experimentally studied the effects of magnetostatic interactions and film thickness on the switching of properties and reversal mechanisms of periodic arrays of elongated $Ni_{80}Fe_{20}$ thin film rings. They showed that the inter-ring spacing strongly affects not only the magnetization reversal process and the switching field distributions but also the transition fields between different equilibrium states. For example, in the case of closely packed ring arrays, sharp transitions were observed from the onion-to-vortex state due to collective magnetization reversal of the rings [25]. They also found that the range of stability of the vortex state is smaller for closely packed ring arrays compared with isolated rings of similar lateral dimensions [25]. Kaur et al. [26] fabricated ring nanostructures from ultrathin Co/Pd multilayers. MFM characterization at room temperature showed that the magnetization orientation and domain structures of nanorings were completely magnetized to saturation. The demagnetized state obtained at zero magnetic probably consisted in a random orientation of spins on each nanostructure [26]. Recently, Edgcombe et al. [27] reported holographic measurements and compared the results with Aharonov–Bohm theory on magnetized cobalt rings; they found both onion and vortex having stable states of magnetization. Wang et al. [23] explained via micromagnetic simulations the MOKE and MFM experimental results obtained from sub-100 nm asymmetrical rings. They observed onion reverse, vortex and onion states during the reversal magnetization. In the case of the ring diameter with very small lateral dimension (30 nm), the vortex state is still presented. Using MOKE and MFM characterization techniques, Ren et al. [28] also studied bi-ring structures. They investigated the effects of the coupling mechanism on the

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[*] Corresponding author.
E-mail address: flo@ipicyt.edu.mx (F. López-Urías).

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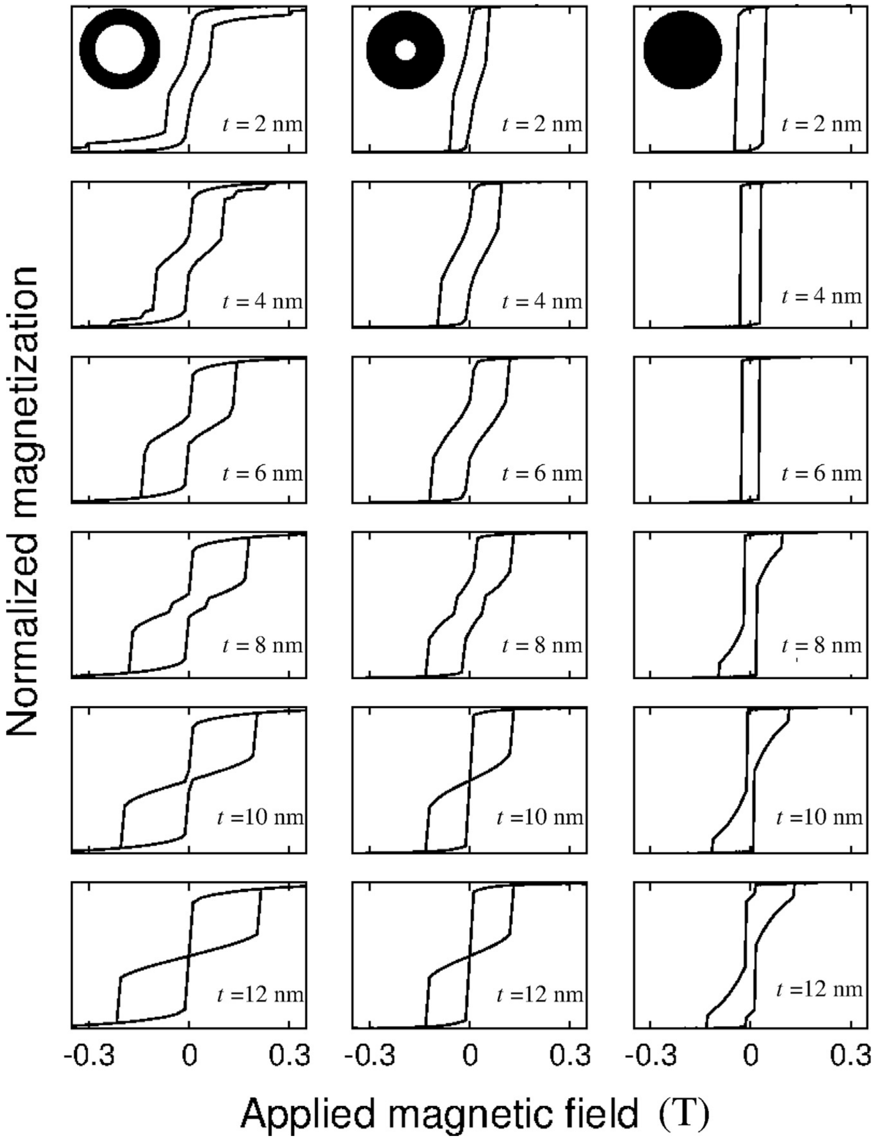

Fig. 1. Hysteresis loops for individual cobalt nanorings with a width of 40 nm (narrow) and 75 nm (wide) in the first and second columns, respectively, and for dots (third column). Different values of the thickness are displayed (t=2–12 nm). All nanomagnets have a diameter of 200 nm. The external magnetic field is applied in plane. Notice that the thin and narrow nanorings (w=40 nm and $t \leq 4$ nm) exhibit multi-switching hysteresis loops, whereas the dot exhibits a single domain reversal magnetization (squared loop) for $t \leq 6$ nm. In both nanorings and dots, the vortex spin configuration appears for $t \geq 8$ nm; however, this becomes the remanent state for $t \geq 12$ nm.

magnetic states and reversal processes when the rings are overlapping, connected and closely spaced. For example, when the rings are overlapped, a metastable magnetization appears due to the vortex chirality of each ring being opposite. However, micromagnetic simulations showed that both same-chirality and opposite-chirality vortex states are possible. To interpret and understand the experimental results, several theoretical studies have been performed to model magnetic nanorings arrangements. For example, Ye et al. [29] investigated two structure models of cobalt nanoring cells (double-nanorings and four-nanorings) using Monte Carlo simulation. The competition between exchange energy and dipolar energy in Co nanorings system was used to explain the emergence deviation of the vortex-type states in the connected regions. Zhang et al. [30] also investigated magnetization reversal processes of magnetic nanorings using the Monte Carlo simulation technique combined with scaling method. They presented a phase diagram for magnetic nanorings with different sizes and radius. In this interesting work, they identified three new types of magnetization reversal processes, namely, an out-of-plane onion state, a twisted triple configuration and a twisted double state. Very recently, using micromagnetic simulations Bickel et al. [31] investigated the formation of 360° domain walls created by the application of a circular magnetic field in ferromagnetic nanorings. The symmetry of the ring as the position of the circular magnetic field was the main parameter to produce the number of domain walls.

To deepen the study of the formation of the different magnetic states formed when an array of nanomagnetic rings is affected by a magnetic field, we investigated double-ring and double-dot arrays using micromagnetic simulations. The hysteresis loops were systematically calculated as a function of the thickness and the inter-nanomagnets distance. The nucleation of different magnetic states, such as vortex, twisted, and onion states and the state named cardioid [32], are analyzed in detail. In the following, the method of calculation and results are presented. The importance of this system for magnetic recording is discussed.