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Journal of Magnetism and Magnetic Materials 242–245 (2002) 996–998

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Investigation of 3D micromagnetic configurations in circular nanoelements

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Abstract

Using 3D micromagnetic simulations the magnetic stable states in circular dots and rings are obtained as a function of the element sizes. Furthermore, the magnetization reversal in a field applied perpendicular to the plane is investigated for Co dots.

Keywords: Computational micromagnetism; Magnetization processes; Magnetic dots

Nowadays in most of the reported MRAM designs, the magnetization of the active device is oriented linearly in the element plane being controlled by the shape of the element-like rectangles or elongated ellipses. It is known [1,2] that for these geometries the presence of the edges domains is responsible for the irrepeatable switching process. These undesirable end effects of a linear element are eliminated for a circular geometry where the magnetization follows a flux closure path. An important challenge today is to find the proper way to create and to manipulate this 'ideal' state. The key issue is to establish the necessary conditions such as the magnetic material parameters and the sizes which will stabilize it. The following numerical simulations are dedicated to investigate the role played by the shape, the size and the crystal anisotropy on the magnetic configuration of individual circular Co dots and rings. Furthermore, the vortex nucleation and reversal mechanism in an out-of-plane applied field is analyzed.

Each magnetic stable configuration of a ferromagnetic system corresponds to a local minimum of the total free energy arising from the crystal, magnetostatic, exchange and Zeeman interaction. Thus, finding a possible magnetic state means to minimize the total energy with respect to the magnetization $\vec{M}$ by preserving its amplitude constant, $|\vec{M}| = M_s$. For the simulations presented here an energy minimization algorithm based on the time integration of the Landau–Lifshitz–Gilbert equation was developed [3]. The physical input parameters have been chosen according to the values known for HCP Co(0 0 0 1) thin films with uniaxial perpendicular anisotropy [4] with the spontaneous magnetization $M_s = 1.4 \times 10^6$ A/m, the exchange constant $A_{ex} = 1.4 \times 10^{-11}$ J/m and the magnetocrystalline anisotropy constant $K_u = 5.0 \times 10^5$ J/m^3. The dimensionless damping parameter α has been taken to be unity as a matter of computational simplification [5]. The real system is discretized into a tri-dimensional array $N_x \times N_y \times N_z$ of uniformly magnetized cubic cells. Since for Co(0 0 0 1), the exchange length is $l_{ex} = \sqrt{2A_{ex}/(\mu_0 M_s^2)} \simeq 3.37$ nm and the Bloch wall parameter is $\Delta_0 = \sqrt{A_{ex}/K_u} \simeq 5.29$ nm a mesh size of 2.5 nm was used. This value was found to be fine enough for the vortex description. A backward implicit Crank–Nicholson method has been used to solve the micromagnetic equations [5].

The competition between the anisotropy energy (crystal and shape), the exchange energy and the externally applied field energy gives rise to different magnetic states whose existence is strongly affected by the magnetic history as well as the element aspect ratio (diameter and thickness). This general feature is confirmed by magnetic force microscopy (MFM) studies performed for circular Co(0 0 0 1) dots [4] and circular polycrystalline Co rings [6]. For both systems two types of magnetic contrasts were clearly evidenced: a strong dipolar contrast emerging from an in-plane

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0304-8853/02/$ - see front matter
PII: S0304-8853(01)01366-X

single-domain configuration and a weak contrast associated with a flux closure configuration. These two zero-field configurations are confirmed by micromagnetic simulations as shown by the magnetization vector plots in the bottom of Fig. 1. Starting from different initial states in the computation, the system relaxes either to the in-plane single domain (Fig. 1 SD) or to the flux closure state (Fig. 1 FC, V).

The MFM results reveal that, for the dots and rings of larger diameter, an irreversible transition from the SD into the flux closure state can be induced by a weak perturbation such as the stray field of a MFM tip. This indicates that in zero field the flux closure state is the energetically lower state. An explanation for this interesting experimental finding is given by analyzing the variation of the calculated energy density as a function of the lateral size. This dependence is compared in Fig. 1 for the dots and rings.

For 5 nm thick circular dots with a diameter above 60 nm, the ground state of the system is the flux closure state (vortex) while the in-plane SD state represents a local energy minimum (Fig. 1a). For the in-plane SD state the total energy density is dominated by the demagnetization contribution due to the appearance of magnetic charges on the lateral surface. In contrast, for the flux closure configuration the demagnetization energy is drastically reduced because the magnetic flux is closed. In this case the dominant energy contribution arises from the exchange energy concentrated in the central vortex. This exchange energy becomes comparable to the demagnetization energy of the SD state only if the diameter of the dot is on the order of the vortex core diameter (about 30 nm in Co [3]). Hence below a critical diameter (60 nm), the single-domain state becomes the ground state of the system. Similar calculations taking into account a large out-of plane magnetocrystalline anisotropy reveals that its presence does not change the characteristics presented above [3].

Regarding now the corresponding curves obtained for the rings having the same thickness and an inner diameter of 50 nm, a different behavior is found. For a circular ring the flux closure configuration is always the ground state of the system since the removal of the vortex core reduces significantly the exchange contribution.

Recently, several studies have been performed on the magnetic behavior of circular elements under a uniform [7] or non-uniform [8] in-plane applied field. However the stability of the vortex under an external field applied perpendicular to the dot plane seems to be interesting from a fundamental point of view, and may be compared to the reversal of bubble domains in continuous films. In order to follow the nucleation and the reversal of the vortex in a perpendicular field, the simulations start from the out-of plane saturated state. The magnetic field is then slowly reduced while recording the hysteresis loop. For each value of the applied field the equilibrium is reached if the residual torque fulfills the condition: $|\vec{m} \times \vec{H}_{\mathrm{eff}}|/M_{\mathrm{s}} < 10^{-6}$.

Using this simulation procedure, the magnetization curves for circular Co dots with 200 nm in diameter and a thickness (t) varying from 5 to 20 nm were obtained for the two cases: with and without perpendicular magnetocrystalline anisotropy (PMA). The thickness range chosen is smaller than 20 nm because for larger values of t, in zero applied field, the presence of the PMA transforms the vortex state into a weak circular stripe structure [3].

The upper part of the hysteresis curves in a perpendicular field as derived from the simulations are

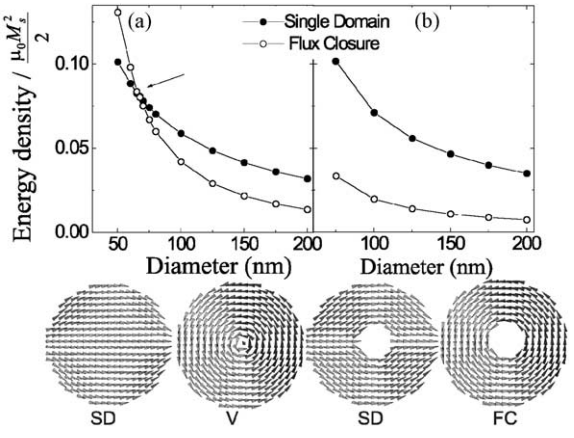

Fig. 1. The variation of the total free energy density as a function of the lateral size of a polycrystalline ($K_{\mathrm{u}} = 0\,\mathrm{J/m^3}$) 5 nm thick dot (a) and ring (b). The magnetization configuration of the single-domain state (SD), the vortex state (V) and the flux closure state (FC).

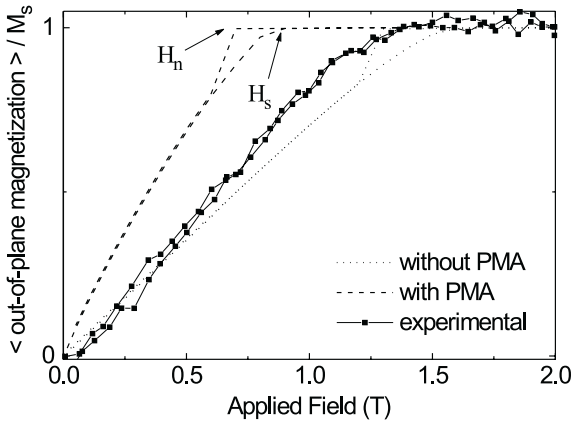

Fig. 2. The simulated perpendicular hysteresis curves of a 15 nm thick circular dot of 200 nm in diameter with PMA, without PMA and as measured experimentally [4].

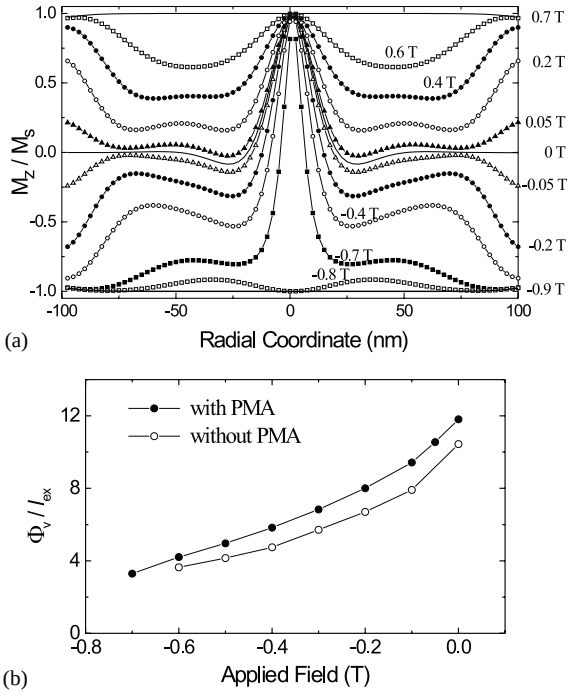

Fig. 3. (a) The evolution of the out-of-plane magnetization as a function of the out-of-plane applied field for a 15 nm thick circular dot of 200 nm in diameter with PMA. (b) The field dependence of the vortex core diameter ϕ_V for dots with and without PMA.

shown in Fig. 2, for 15 nm thick individual dots. The behavior is qualitatively the same for the two cases: with and without PMA. The details of the magnetization reversal are illustrated in Fig. 3 for a circular dot with large PMA. The line scan profiles across the dot diameter of the out-of-plane magnetization are represented for several values of the applied field. Starting from the positive saturated state and reducing the field value, a vortex-like state is nucleated at H_n giving rise to a small jump in the hysteresis loop as indicated in Fig. 2. Because of the symmetry of the system the central part develops into a vortex whereas the outer region rotates towards the dot plane in order to avoid the surface charges. In zero applied field, the full vortex structure is developed. Upon reversing the perpendicular applied field, first the magnetization along the dot border reverses, while the vortex itself remains stable up to a relatively large field value of $-(0.6–0.7)$ T. The reversal of the outer region leads to a compression of the vortex core with increasing reverse field as shown in Fig. 3b. Here, the vortex core diameter (ϕ_V) is defined as the radial region where the out-of-plane magnetization is positive. Most likely, when a critical radius is reached the vortex core cannot be compressed any further due to the increase of the exchange energy. This will finally leads to the reversal of the vortex core and to the negative saturation state. From the calculation (Fig. 3b) this critical radius is estimated to be of order of $(3–4)l_{ex}$.

As noted previously the presence of the PMA does not modify the reversal behavior, it only leads to a shift in the nucleation field (Fig. 2). The relatively strong PMA considered here stabilizes the perpendicular saturated state up to a much lower field value with a shift corresponding to the magnetocrystalline anisotropy field $H_u = 2K_u/(\mu_0 M_s) \simeq 0.7$ T.

A comparison of the calculated perpendicular hysteresis curves with the experimental curve recorded for a large number of Co(0 0 0 1) circular dots having the same size and being arranged in a square array [4] (Fig. 2) is somewhere between the two simulated curves for an individual dot. These differences are attributed to possible defects of the real system, the dipolar interaction between the dots and the influence of the temperature which are neglected in the simulation.

In summary, the stable magnetic configurations for circular Co dots and rings have been compared using numerical simulations. While for the rings the flux closure state is always the ground state for the dimensions considered, in the case of the dots the ground state evolves from a vortex state into a single-domain state below a critical diameter. Furthermore, the evolution of the magnetization distribution under perpendicular applied field has been investigated for circular dots. It is found that the vortex is stable up to relatively large reversed field value.

This work was partially supported by the EC program 'Magnoise' No IST-1999-11433 and EC program 'NanoPTT' No G5RD-CT-1999-00135.

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