Vortex States Stability in Circular Co(0001) Dots

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***Abstract*—The possible magnetization configurations of individual circular Co(0001) dots are investigated by means of 3D micromagnetic simulations as a function of dot dimensions. In zero applied field, the vortex state corresponds to the ground state for diameters larger than 60 nm and up to a thickness of 25 nm where a transition into a weak stripe structure occurs.**

***Index Terms*—Co(0001), MFM, micromagentism, vortex state.**

I. Introduction

RECENTLY many experiments have been performed on square [1] rectangular [2], elliptical [3] circular [4] or ring [5] shaped flat elements of submicron lateral sizes. One particular point of interest is to delineate the boundaries between the possible stable and metastable magnetization configurations as a function of system size (thickness, lateral width) and magnetization history. In this context, the transition between the single domain state and a vortex-like state have attracted considerable attention. In the vortex configuration the magnetization tries to reduce its in-plane demagnetization shape energy as much as possible by forming an in-plane circular magnetization path. This leads to a central vortex where the magnetization points perpendicular out of the element plane. Such singularities are known for some time [7], however only recently clear direct experimental evidence has been given for their existence using Lorentz microscopy [8] and magnetic force microscopy (MFM) [8], [9]. Complementary evidence was found by studying hysteresis loops [4] and by using electron holography [10]. While many studies were performed on polycrystalline NiFe [9], NiFeMo [4] or Co [3] materials for which magneto-crystalline anisotropies are negligible, not many investigations are reported for epitaxial materials having a strong **P**erpendicular uniaxial **M**agneto-crystalline **A**nisotropy (PMA) [6], [10].

Here a numerical analysis is presented on the single domain (SD) to vortex-like (V) and the vortex-like to stripe domain transition for epitaxial Co(0001) dots whose uniaxial magneto-crystalline easy axis is oriented perpendicular to the film plane. The uniaxial anisotropy energy is fairly large but still smaller than the demagnetization field energy [1]. The recent MFM investigations [6] indicate the existence of an in-plane single domain state and a vortex-like configuration in circular dots of $\phi = 200$ nm diameter and of thickness $t = 10$–35 nm.

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II. Micromagnetic Calculation

The stable magnetization configurations were obtained by minimizing the total free energy of the system, which includes contributions from the magnetocrystalline anisotropy, the demagnetization, the exchange and the Zeeman energy. The minimization is carried out with respect to $\overrightarrow{M} = M_s \overrightarrow{m}$ under the constraint $|\overrightarrow{m}| = 1.0$. Starting from a given configuration, the system proceeds toward a local minimum by following the states according to the Landau-Lifshitz-Gilbert equation (LLG) [7]. The real system is discretized into $N_x \times N_y \times N_z$ cubic cells of constant magnetization. The cell size is 2.5 nm, which is smaller than the characteristic magnetic lengths of Co. Using the material parameters of Co, saturation magnetization $M_s = 1400$ emu/cm^3, exchange constant $A_{\rm ex} = 1.4 \times 10^{-6}$ erg/cm, magnetocrystalline anisotropy constant $K_u = 5 \times 10^6$ erg/cm^3, the exchange length is $l_{\rm ex} = \sqrt{A_{\rm ex}/(2\pi M_s^2)} \cong 3.37$ nm and the Bloch wall width parameter is $\Delta_0 = \sqrt{A_{\rm ex}/K_u} \cong 5.29$ nm. The magnetostatic energy is evaluated in the approximation of uniform magnetized cubic cells and the demagnetization field is substituted by its value averaged over the cell. The fast Fourier method is implemented for the stray field evaluation. The numerical stability of the time integration of the LLG equation is assured by the use of Crank-Nicholson method. A constant time step of $dt = 0.1$ ps has been used and the damping parameter was set to $\alpha = 1.0$ since we are only interested in the static stable state.

III. Results and Discussion

Continuous Co(0001) films with perpendicular uniaxial magneto-crystalline anisotropy (K_u) are characterized by the formation of a stripe domain structure whose period scales with the film thickness. For these films, the magnetization starts to cant from the perpendicular orientation toward the in-plane orientation below a thickness of 60 nm and below 20–25 nm the magnetization is fully in-plane [11]. A reduction of the lateral sizes of such films down to the submicron scale has shown that stripe domains develop in thick dots similar to the continuous films and that a single bubble domain can be stabilized in the center [1]. In the canted thickness range circular ring domains develop [1]. More interesting is the region of $t < 25$ nm, for which the continuous films are in-plane magnetized. The reduction of the lateral sizes induces additional in-plane demagnetization fields, which will support the PMA but be in competition with exchange energies. The MFM investigations of arrays of epitaxial circular Co(0001) dots [6] have shown that different magnetic states can be induced depending on

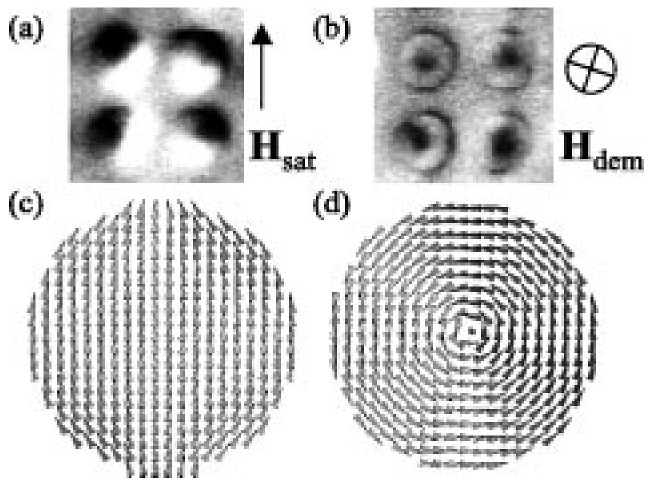

Fig. 1. MFM images ($0.8\ \mu$m $\times$ $0.8\ \mu$m) corresponding to (a) an in-plane remanent state and (b) an out-of-plane demagnetized state for dots of $t = 10$ nm and $\phi = 200$ nm. Top view of (c) a single domain and (d) a vortex-like state obtained from 3D micromagnetic calculations.

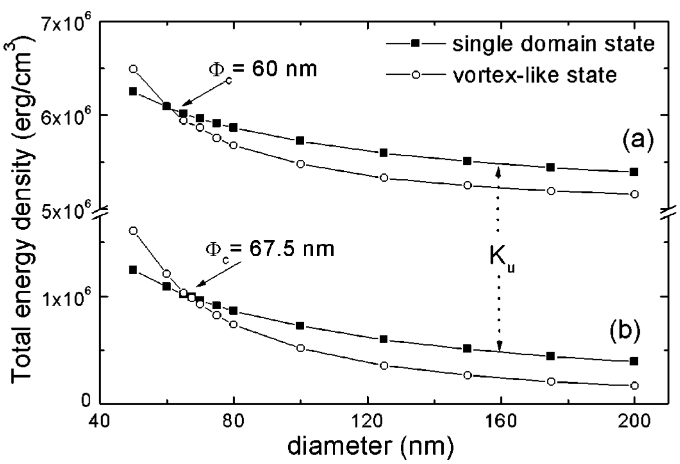

Fig. 2. The total free energy density of the V and SD state as a function of the dot diameter for $t = 5$ nm and for dots (a) with $K_u = 5 \times 10^6$ erg/cm^3 and (b) with $K_u = 0$.

the dot dimensions as well as on the magnetic history. In Fig. 1 two examples are shown for $t = 10$ nm after (a) in-plane saturation and (b) out-of-plane demagnetization. The strong dipolar contrast in Fig. 1(a) is interpreted as a single domain state while the weaker contrast in Fig. 1(b) with a dark spot in the center is indicative of a vortex-like state. A similar contrast has already been observed recently by MFM [8], [9] and Lorentz microscopy [8] for permalloy dots and has been correlated with a vortex state.

In order to investigate the possibility of the formation of a vortex-like state in Co(0001) dots and the role of the PMA, 3D micromagnetic calculations were performed. Using different starting configurations, the system relaxed either into a single domain state (Fig. 1(c)) or a vortex-like state (Fig. 1(d)). In the thickness range investigated numerically, between $t = 5$ nm to 25 nm and for dot diameters of $\phi = 60$ nm to 200 nm, the vortex-like state was found to be the energetically lowest state. The dependence of the total energy density of the SD and the V states at zero applied field and for $t = 5$ nm is shown in Fig. 2 as a function of ϕ. Here, two cases are compared, Co dots with strong PMA (Fig. 2(a)) and those having zero magneto-crystalline anisotropy (Fig. 2(b)). The dependence on ϕ in both cases is quite similar, except that the total energy density of the SD and V dots with PMA is shifted upwards by the amount of K_u (most spins are in-plane). The presence of the PMA does not influence the ground-state configuration very much, nor the transition from the V state toward the SD state, which takes place at a critical diameter ϕ_c of 60 nm for Co(0001) dots with PMA and at 67.5 nm for dots with $K_u = 0$.

This weak dependence on the PMA is related to the fact that in this thickness range no tendency exists for the magnetization to cant out-of-plane, so the cost of energy to establish a vortex state with or without anisotropy is about the same. Typical domain widths of stripe domains would be at least twice as large as the film thickness in this t range. Hence, the out-of-plane demagnetization fields will keep the magnetization parallel to the dot surface. Thus, the 200 nm diameter Co dots behave like in-plane isotropic elements and the transition from the V to the SD state is determined by the competition between the in-plane shape demagnetization energy which dominates in the SD state and the exchange energy which is the dominant energy contribution in the vortex state. However, the presence of the PMA lowers the total energy density of the vortex state slightly, since the spins inside the vortex itself point into the magneto-crystalline easy axis and can lower their PMA energy. Close to the critical diameter, this gain in energy is most pronounced, since the relative volume fraction of the vortex is large. As a consequence the critical diameter for the transition into a SD state is somewhat lower. It is noted as well, that due to the larger value of the saturation magnetization M_s in Co, this critical diameter is smaller than the one observed in [4] for the same t.

From Fig. 2 it is seen that above the critical diameter the ground state of the system is the V-like state while the SD state corresponds to a local energy minimum. Generally, the magnetic configuration corresponding to a local energy minimum can be induced in the experiment following specific magnetization histories. In the MFM measurements performed on the 200 nm diameter Co(0001) dots [6], the SD and V states are observed simultaneously with a larger probability of SD state to exist after in-plane saturation. However, those SD states are found to be metastable in agreement with the micromagnetic calculations. Small perturbations, such as the stray field from the MFM tip, can induce a irreversible transition into the V-like state.

It is interesting to compare the critical diameter of 60 nm for the V to SD transition with the extension of the vortex core which is approximately half the size at $t = 5$ nm. In Fig. 3(a), a line scan across the diameter is shown for the out-of-plane magnetization component M_z. Three cases are compared, the numerical solution for uniaxial Co(0001)(square), the numerical solution for Co with $K_u = 0$ (open circle) and an analytical approximate expression derived in [12] (full line). The profile obtained from the numerical calculation in the case of $K_u = 0$ is fit quite well by the analytical profile. The deviations with increasing diameter are a result of the approximate formulation of the vortex demagnetization fields in the analytical expression. For the case of Co(0001) with PMA, the deviations are slightly more pronounced. The full width of the vortex diameter (D_V)

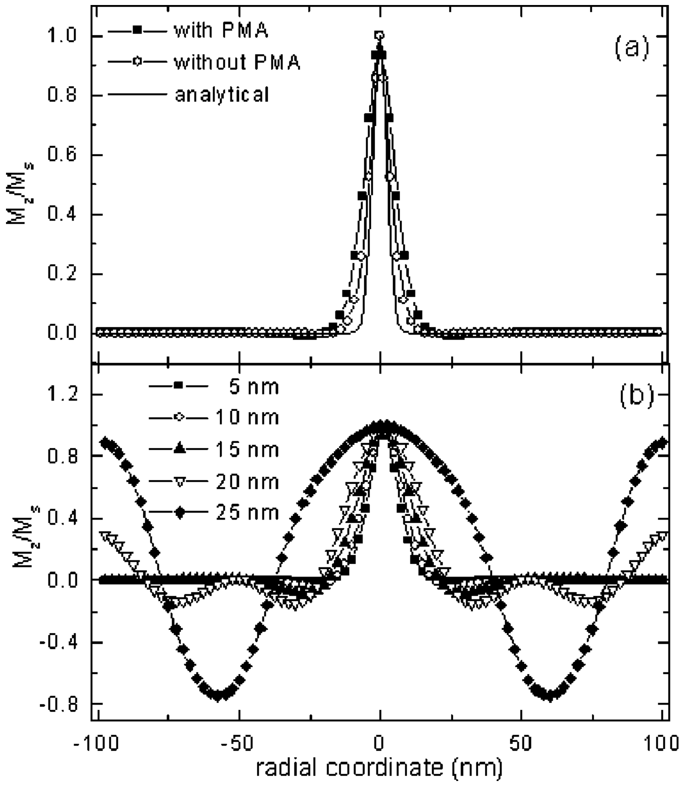

Fig. 3. (a) Line scan of the out-of-plane magnetization component M_z across the diameter ($t = 5$ nm, $\phi = 60$ nm) for three different cases as discussed in the text. (b) M_z line scan profiles across the diameter as a function of dot thickness for $\phi = 200$ nm in the case of epitaxial dots with PMA.

in this case is 37.5 nm, which is larger than for $K_u = 0$ with $D_V = 32.5$ nm. It is noted that this is approximately the value which was found in [10] using electron holography on triangular shaped Co thin film elements. Furthermore, D_V does not vary much across the dot thickness for the small values investigated here, nor as a function of the dot diameter as immediately obvious. However upon increasing the film thickness, the out-of-plane demagnetization field decreases and hence the exchange energy widens the vortex. This is shown in Fig. 3(b), for the M_z profile across the diameter for $\phi = 200$ nm and for t varying from 5 nm to 20 nm as deduced from simulation.

Upon further increasing the thickness, a transition from the vortex state into a weak circular stripe domain state takes place due to the presence of the PMA. The size of the central region with the magnetization pointing upwards has increased drastically to an almost domain like region, see Fig. 3(b). Already at $t = 15$ nm and 20 nm small oscillations of M_z across the radius set in, but the magnetization is still predominantly in-plane. These oscillations have developed at $t = 25$ nm into a circular weak stripe structure, with a period which is about half the period of the oscillations at $t = 20$ nm. A similar concentric ring structure has been reported in [1] for 25 nm thick square Co dots. $t = 25$ nm corresponds to the thickness range, where in the continuous epitaxial Co(0001) films a reduction of the PMA energy is achieved by formation of a weak stripe domain structure with the magnetization canted out of the plane [11]. The lateral confinement of this weak stripe structure induces a circular arrangement of the domains in order to reduce the in-plane demagnetization field.

IV. Conclusion

In conclusion, the ground state magnetization configurations for epitaxial Co(0001) dots have been investigated by 3D numerical micromagnetic calculation. A single domain as well as a vortex-like state are found, where the V state is the energetically lower state for $t = 5$–25 nm and $\phi = 60$ to 200 nm. For $t = 5$ nm the transition from the vortex to the SD domain state was found at a critical diameter of 60 nm which is approximately twice the diameter of the vortex. This transition as well as the vortex profile are only weakly dependent on the PMA. Furthermore, the vortex diameter remains rather unchanged as a function of thickness. At a thickness of 25 nm, the vortex widens up considerably, and the magnetization configuration transforms from the vortex-like state into a circular weak stripe state due to the presence of the strong perpendicular anisotropy.

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