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M. Natali, A. Lebib, Y. Chen, I. L. Prejbeanu, and K. Ounadjela

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Configurational anisotropy in square lattices of interacting cobalt dots

M. Natali,[a] A. Lebib, and Y. Chen[b]
LPN, CNRS, Route de Nozay, 91460 Marcoussís, France

I. L. Prejbeanu and K. Ounadjela[c]
IPCMS–GEMME (UMR 7504 CNRS-ULP), 23 rue du Loess, 67037 Strasbourg, France

Magnetostatic coupling effects are investigated in square lattices of polycrystalline circular Co dots as a function of dot diameter, spacing, and thickness. We observe a quadratic anisotropy for closely spaced dots when the dot thickness exceeds 15 nm, correlated to a change in the magnetization reversal process from coherent rotation to vortex nucleation/annihilation. To understand the observed anisotropy micromagnetic simulations have been performed which show that vortex nucleation is strongly dependent on the micromagnetic configurations. [DOI: 10.1063/1.1447176]

Patterned magnetic media are currently of great interest for realization of high-density data storage devices. The fabrication of arrays with densities up to 65 Gbit/in.[2] has been demonstrated.[1] However for such high densities crosstalk between adjacent elements, associated with magnetostatic interactions, can become a critical factor limiting the application. Magnetostatic coupling between elements can lead to several effects such as alteration of the switching field distribution and nucleation cascades.[2] Moreover for square lattices of in-plane magnetized dots quadratic anisotropies have been observed because of interactions.[3] It is believed that this latter effect is due to nonuniformities in the magnetization distribution of the dots but no detailed investigation has yet been given.

In the present work we analyze quadratic anisotropies in square lattices of polycrystalline circular Co dots as a function of dot diameter, spacing, and thickness. The quadratic anisotropy is only observed for dot thicknesses above 15 nm and in correlation with the formation of magnetic vortices. The experimental results are confirmed by micromagnetic simulations which show that different magnetic configurations are stabilized by the interactions and strongly influence the vortex nucleation process.

Arrays of polycrystalline circular Co dots with various dot diameters D, thicknesses t, and dot spacings S, defined as the distance between dot centers, have been fabricated by nanoimprint lithography and liftoff.[4] The dots are arranged on square lattices with areas of $150\times150\ \mu m^2$. Nominal geometrical parameters were $D/S=150/200$, 250/300, 500/600, 500/750, 500/1000, and 1000/1100 (all values in nm) and $t=10$ nm, 15 nm, 20 nm, 30 nm, and 50 nm. Precise values of D, S were measured by scanning electron microscopy. The samples were characterized by magneto-optic Kerr effect (MOKE) measurements, recording hysteresis loops in longitudinal geometry at room temperature. The focal spot of the laser on the sample had a diameter of about 100 μm.

Hysteresis loops for dots with different thicknesses are shown in Fig. 1. A transition is observed from square loops below $t=15$ nm to loops having low remanent magnetization above $t=30$ nm. For the square loops magnetization reversal occurs by coherent rotation of a single-domain state as has been confirmed by magnetic force microscopy imaging reported elsewhere.[5] On the contrary for loops with low rema-

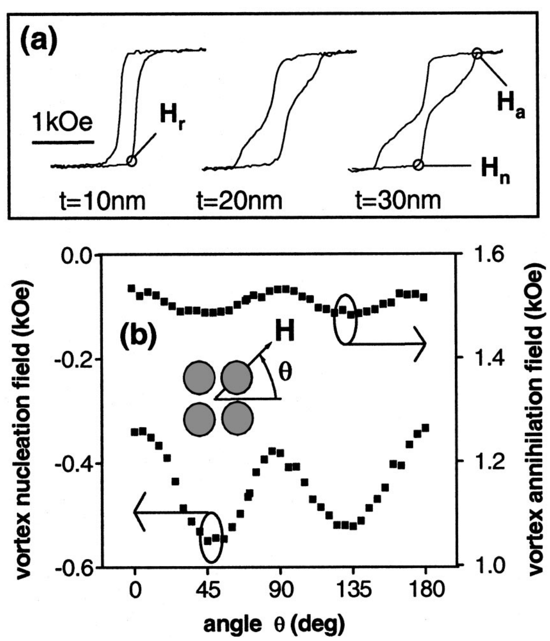

FIG. 1. (a) MOKE hysteresis loops for dots with $D=250$ nm, $S=300$ nm, and different thicknesses. (b) Vortex nucleation and annihilation field vs angle of the applied field ($D=170$ nm, $S=200$ nm, $t=30$ nm).

[a]Present address: ICIS-CNR, Corso Stati Uniti 4, 35127, Padova, Italy; electronic mail: natali@ictr.pd.cnt.it
[b]Electronic mail: young.chen@lpn.cnrs.fr
[c]Present address: SPINTEC-CEA/DRFMC/SP2M, 17 Avenue des Martyrs 38054 Grenoble, France.

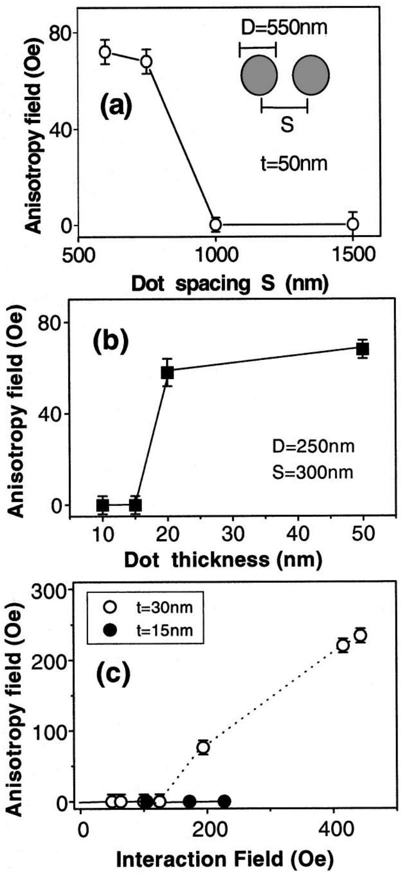

FIG. 2. Quadratic anisotropy field as a function of: (a) dot spacing, (b) dot thickness, and (c) interaction field.

nence reversal occurs via nucleation and subsequent annihilation of a magnetic vortex. The flux-closure configuration of the vortex state is responsible for the drop of magnetization at remanence. At intermediate thicknesses, i.e., 20 nm, the remanent magnetization is high but reversal still takes place by nucleation of vortices in a positive applied field. A more detailed description of the above transition is reported elsewhere.[4,5]

Here we focus on the angular dependence of the critical fields characterizing the reversal mechanism: the vortex nucleation and annihilation fields H_n, and H_a, and the reversal field H_r, respectively defined in Fig. 1(a). To this purpose MOKE loops are recorded for different in-plane angles of the applied field. In Fig. 1(b) we plot the vortex nucleation and annihilation fields versus the applied field angle. Oscillations with 90° period are observed, corresponding to a quadratic in-plane anisotropy. The two easy axes coincide with the array axes while the two hard axes correspond to the array diagonals. We want to stress that the quadratic anisotropy in general is much more pronounced for the vortex nucleation field than for the vortex annihilation field.

In Fig. 2(a) we report the dependence of the quadratic anisotropy field on dot spacing. A decrease is observed with increasing dot spacing, suggesting that magnetostatic coupling between the dots is the cause of the anisotropy. The thickness dependence of the anisotropy is shown in Fig. 2(b). Note that the anisotropy field is zero for $t = 15$ nm and in-

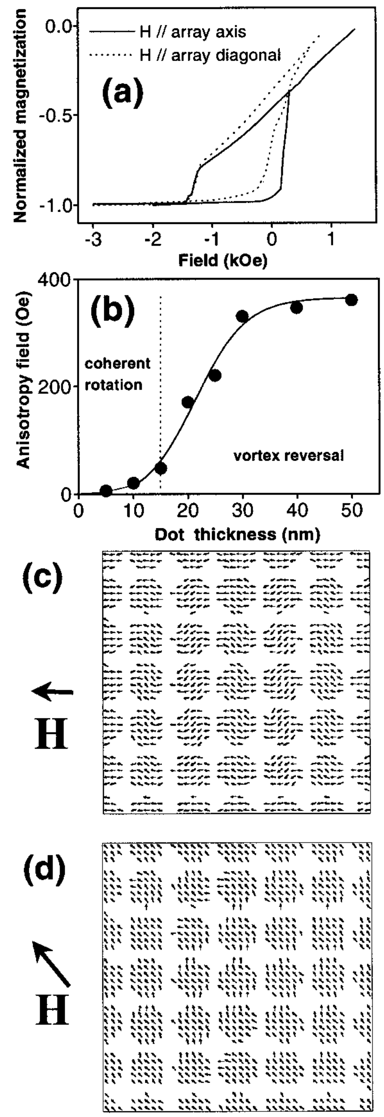

FIG. 3. Micromagnetic simulations for an array of dots with $D = 170$ nm, $S = 200$ nm. (a) Minor loops for $t = 30$ nm: (solid curve) field applied along the array axis, (dotted curve) field along the array diagonal. (b) Calculated anisotropy field vs dot thickness. (c) Typical micromagnetic configurations before vortex nucleation: field along array axis, (d) field along array diagonal.

creases abruptly for $t > 15$ nm, in correlation with the observed change in the reversal mechanism. In Fig. 2(c) the anisotropy field is plotted as a function of the calculated dipole interaction field[6] $H_{\mathrm{int}} = 4.2 M_s V/S^3$, where V is the dot volume and $M_s = 1400$ emu cm^{-3} the saturation magnetization density of Co. As expected, the anisotropy increases with increasing interaction field for dots with $t = 30$ nm, starting at about 100 Oe. On the contrary for dots with $t = 15$ nm the anisotropy field remains zero up to relatively high fields, comparable to those for 30 nm thick dots. The absence of quadratic anisotropy for 15 nm thick dots therefore cannot be attributed to the relative weakness of the interaction field for these dots.

In Ref. 3 the quadratic anisotropy was attributed to unsaturated parts inside the dots which give rise to multipolar terms in the interaction field. Indeed it is known that for uniformly magnetized circular dots on a square lattice the dipolar interaction field is isotropic.[7] Our results suggest that the unsaturated parts are in close relationship with vortex states.

To clarify further this point we performed micromagnetic simulations using the public domain code oommf.[8] Simulations are made for arrays of 5×5 dots using ''fixed'' boundary conditions: first the demagnetization field, arising from the finite size of the array is compensated by adding appropriate charge distributions at the boundary of the simulated zone. Second, to describe the oscillating part of the magnetic field along the boundary, half dots with fixed magnetization are added. These boundary conditions reasonably approximate the behavior of an infinite array close to vortex nucleation and annihilation. The vortex nucleation and annihilation fields are determined by calculating minor hysteresis loops, sweeping the field from negative saturation to a field above the vortex nucleation field and back again. In Fig. 3(a) minor hysteresis loops are shown for the field applied along the array axis and along the array diagonal. Clearly vortex nucleation is favored when the field is parallel to the array diagonal and a value of 320 Oe can be determined for the quadratic anisotropy field, which compares reasonably well with the experimental value of 220 Oe in Fig. 1(b). Moreover the vortex annihilation field is found not to depend on the field direction, in qualitative agreement with the small anisotropy values measured for the annihilation field. In Fig. 3(b) the calculated anisotropy field is plotted versus dot thickness. A marked increase occurs starting at $t=15$ nm in agreement with the experimental results in Fig. 2(b). The simulations also permit us to establish that at $t=15$ nm a transition occurs in the reversal process from coherent rotation to vortex nucleation/annihilation. Therefore the marked increase in the cubic anisotropy is indeed correlated to the onset of vortex formation.

In Figs. 3(c) and 3(d) we consider the micromagnetic configurations just before vortex nucleation. When the field is applied along the array axis [Fig. 3(c)] magnetization starts to reverse in the center of the dots. The magnetization at the dot edges remains aligned with the applied field direction due to interaction with the nearest neighbor dots lying along the field direction. On the contrary when the field is parallel to the array diagonal [Fig. 3(d)] the interaction with nearest-neighbor dots tilts the magnetization at the dot edges towards the array axes. These results show that a configurational anisotropy exists that is induced by interactions.

To understand the relationship between quadratic anisotropy and vortex formation we note that, contrary to coherent rotation, vortex formation is a highly inhomogeneous process and therefore depends strongly on the detailed micromagnetic configurations prior to vortex nucleation. Indeed since vortices are known to nucleate at dot edges we expect that they form more easily from the micromagnetic configuration shown in Fig. 3(d) than from the one shown in Fig. 3(c).

Finally let us consider vortex annihilation. Vortices are annihilated when the vortex core is pushed out from the dot under the action of the applied field.[5] The simulations show that this process is the same, irrespective of the in-plane direction of the applied field. The weakness of the quadratic anisotropy for H_a therefore can be explained by the absence of a configurational anisotropy during vortex annihilation.

In conclusion we have observed a quadratic in-plane anisotropy in square lattices of interacting circular cobalt dots that occurs in correlation with vortex formation. Micromagnetic simulations show that the quadratic anisotropy is the result of a configurational anisotropy induced by interactions together with the high sensitivity of the vortex nucleation process on details of the micromagnetic configurations.

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