Effects of asymmetric dipolar interactions between elliptical ferromagnetic nanomagnets in artificial spin-ice structures

J.M.Porro[1], M.Grimsditch[1][2], V.Metlushko[3], O.Idigoras[1], A.Berger[1], P.Vavassori[1]

[1] CIC nanoGUNE Consolider, Tolosa Hiribidea 76, E-20018, Donostia-San Sebastián
[2] Materials Science Division, Argonne Natl. Lab., 9700 South Cass Ave., Argonne, IL 60439
[3] Department of Electrical and Computer Engineering,University of Illinois at Chicago,Chicago IL 60607

t.porro@nanogune.eu

At the present time, arrays and networks of closely-spaced, dipole-coupled, single-domain nanomagnets are being intensively studied. For applications of nanomagnets in hard disk drives and magnetic random access memories the challenge is generally to avoid magnetic dipole interactions between the individual elements in such arrays, because they are a limiting factor for the achievable data storage density. Contrary to these application related aspects, the dipolar interaction between nanomagnets can be utilized to form a so-called 'artificial spin-ice' structure, which has been recently offered a novel approach to understanding and exploiting the properties of disordered systems, such as liquids, glasses and disordered magnets that are governed by competing interactions leading to frustration effects [1]. Moreover, dipolar interactions have been utilized to realize magnetic quantum-dot cellular automata systems, which are networks of dipole-coupled nanomagnets designed for digital computation [2]. In our studies we demonstrate that dipolar interactions in such arrays can be exploited to induce and control magnetization states and reversal paths in nanomagnets that are completely different from those occurring in isolated nanomagnets.

We fabricated and studied arrays of elliptical ferromagnetic (material Py 25 nm thick) nanomagnets of 700 nm length and 200 nm width, arranged in groups of four to form square units. The square units are organized in a checkerboard pattern (see scanning electron micrograph in Fig. 1). The characterization of the magnetization reversal process in our sample was performed by means of our home-built Magneto-Optical Kerr Effect (MOKE) setup and magnetic force microscopy (MFM) for different orientations and intensities of the applied magnetic field. The experimental results are compared to those obtained from micromagnetic simulations.

In general, the magnetic measurements show that the magnetization reversal process in the nanomagnets changes substantially by applying the external magnetic field parallel to (within $\pm 0.2^{o}$) or at an angle from one of the sides of the squares forming the array (see hysteresis loops in the bottom panel of Fig. 2). The simulations performed on a unit cell of the spin-ice array confirm this behavior (see hysteresis loops in the top panel of Fig. 2): when the magnetic field is applied away from the symmetry axes of the ferromagnetic nanomagnets the formation and rotation of a so-called 'S' single domain state is observed in all the nanomagnets, whereas when the field is applied parallel to their symmetry axis the formation of a so-called 'C' state, which evolves into a single vortex state, is observed in the two elliptical nanomagnets having their short axis parallel to the field (see micromagnetic configurations in Fig. 3).

We analyzed the role played by each of the ferromagnetic nanomagnets in the magnetization reversal process, finding that the formation of the vortex state in the two nanomagnets with short axis parallel to the field is due to the asymmetry of the stray field generated by the other two nanomagnets in the spin-ice unit cell.

Confirmation of the existence of these intermediate metastable states was obtained using magnetic force microscopy after applying a suitable field sequence (see magnetic force micrographs in Fig. 3).

Our studies demonstrate that it is indeed possible to control the magnetization states in elliptical ferromagnetic nanoislands by placing localized magnetic field sources in their proximity, and that such localized field sources can be easily facilitated within an appropriate array structure.

We acknowledge funding of the Department of Industry, Trade, and Tourism of the Basque Government and the Provincial Council Gipuzkoa under the ETORTEK Program, Project No. IE06-172, as well as the Spanish Ministry of Science and Education under the Consolider-Ingenio 2010 Program, Project CSD2006-53. P.V. also acknowledges support through the Marie Curie International Reintegration Grant within the 7th European Community Framework Programme, (Grant AgreementNo. PIEF-GA-2008-220166) and finally the Basque Government for the Formación de Investigadores fellowships No. BFI09.284 and BFI09.289.

References

[1] R. F. Wang et al., Nature **439**, 303 (2006)
[2] A.Imre et al., Science **311**, 205 (2006)

Figures

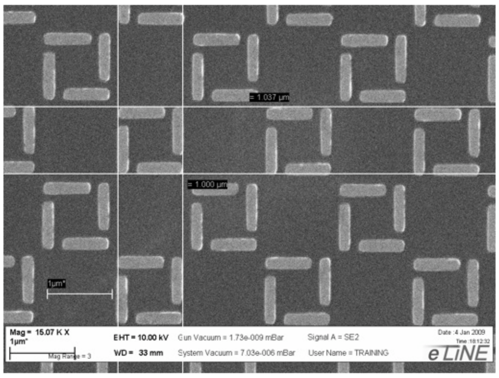

Fig.1: SEM image of the fabricated and analyzed sample.

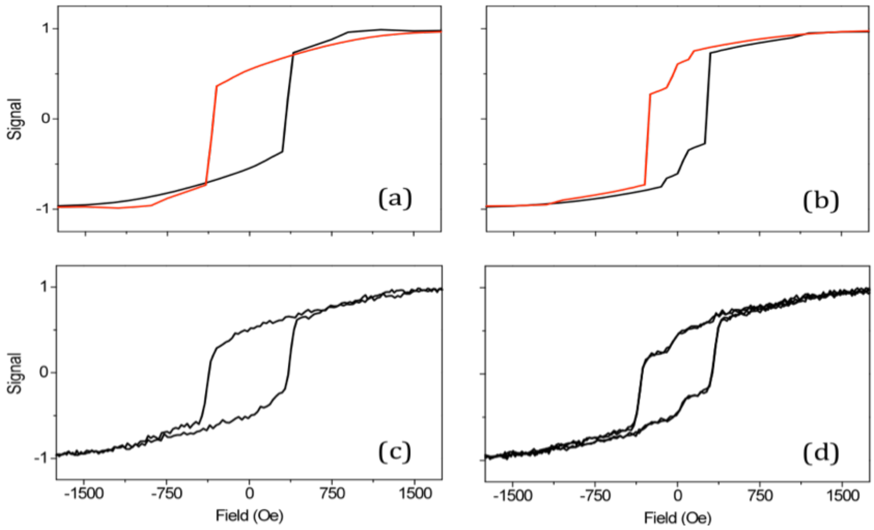

Fig.2: Calculated longitudinal-MOKE hysteresis loops for the off-axis (a) and on-axis (b) external applied magnetic field, and the corresponding measured hysteresis loops for the off-axis (c) and on-axis (d) cases.

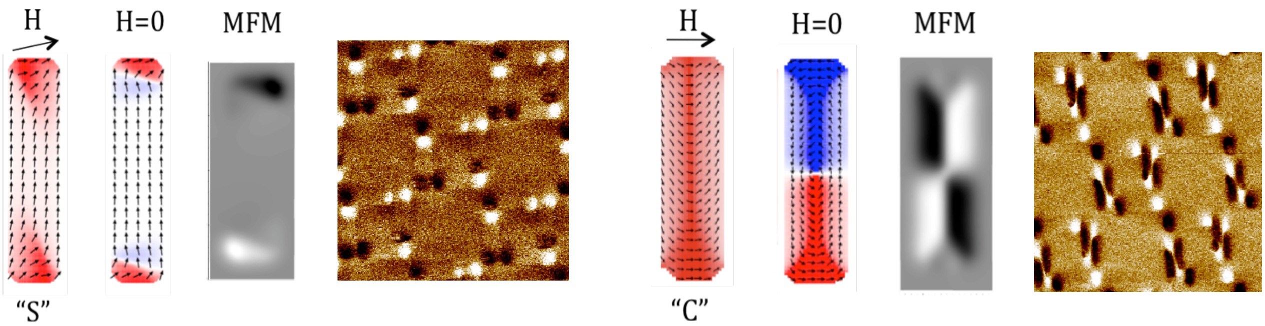

Fig.3: Calculations of the seed and remanent (H = 0) magnetization states in an interacting nanomagnet and the corresponding calculated and measured MFM images for the off-axis (left) and on-axis (right) directions of the applied magnetic field.