

Breakdown of Ising-like behavior of ferromagnetic nano-islands in artificial spin-ice structures driven by asymmetric dipolar interactions

J.M.Porro⁽¹⁾, M.Grimsditch⁽¹⁾⁽²⁾, V.Metlushko⁽³⁾, A.Berger⁽¹⁾, P.Vavassori⁽¹⁾⁽⁴⁾

⁽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

⁽⁴⁾ Ikerbasque, Basque Science Foundation, E-48011, Bilbao

t.porro@nanogune.eu

Systems governed by competing interactions producing frustration phenomena are being intensively investigated since their study can lead to an improved understanding of the basic physics of disordered states of matter. In general, disordered states are so overwhelmingly complicated that they do not yield a clear picture at the microscopic scale of the forces that lead to frustration. Arrays of lithographically fabricated interacting nano-scale single-domain magnets arranged to produce frustration, the so-called artificial spin-ice structures, have been used to construct particularly simple model systems for the investigation of fundamental physics aspects related to frustration [1]. Understanding the interactions between closely spaced nano-magnets is also crucial for present and future applications such as, ultrahigh density memories for data storage applications and magnetic quantum-dot cellular automata, which are networks of dipole-coupled nano-magnets designed for digital computation [2].

In artificial spin-ice systems, ferromagnetic nano-islands are assumed to behave like single dipoles showing Ising-like properties; i.e., a bi-stable magnetization reversal behavior. Such behavior is normally ensured via shape anisotropy of each island (the self-energy of the island's magnetic moment, which is controlled by its shape), which is used to force the magnetic moment to align along its long axis. This assumption neglects crucial aspects of the physics involved: the dipolar field coupling between adjacent islands is not uniform over the whole island and it might not be spatially symmetric.

We show in this study that the non uniform distribution of the dipolar interaction field can induce formation of non-uniform magnetization distributions during system remagnetization even in magnetic nano-islands that are stable in the single-domain state when isolated, thus leading to a breakdown of the basic assumption of Ising-like behavior. This is shown in Figs. 1, 2 and 3 that display magnetic force microscopy images of the remnant magnetic state, after saturation in a magnetic field H applied as indicated, of chiral artificial spin-ice structures made of elongated Permalloy (FeNi 20/80 alloy) ferromagnetic nano-islands of different aspect ratios, fabricated by electron-beam lithography. Despite of the high aspect ratio, viz., shape anisotropy, non-uniform magnetization vortex states are observed in some of the nano-islands. We demonstrate that the observed breakdown of the expected Ising-like behavior that leads to the nucleation of vortex states of well defined chirality is determined by the interplay between competing asymmetric dipolar interactions and magnetization dynamics of the individual nano-elements.

From a different point of view, our study demonstrates that localized magnetic field sources can be used to actively induce and finely control the magnetization states and reversal paths of nano-magnets, and that such localized field sources can be easily facilitated within the 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, IKERBASQUE, the Basque Science Foundation and Basque Government fellowship No. BFI09-289.

References

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

Figures

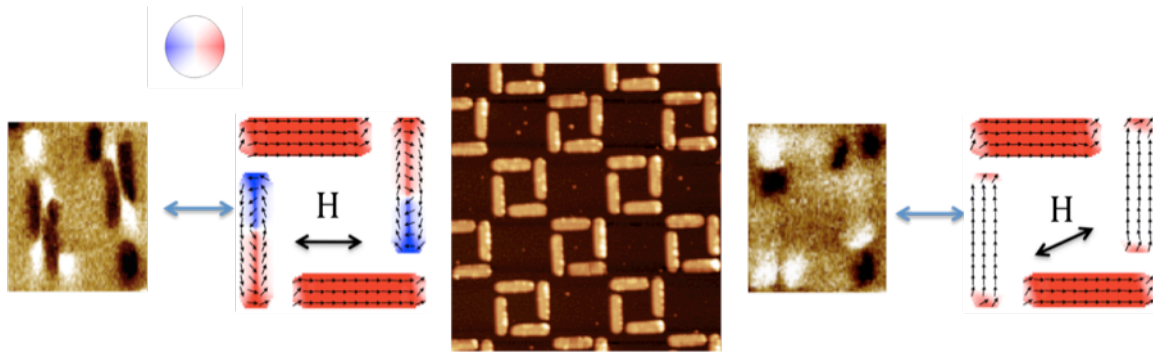


Fig.1: AFM topography image (center) of a checkerboard array of ferromagnetic nanoislands arranged in square units with vertical and horizontal bars of 700nm length ($AR=4$) flanked by micromagnetic simulations and MFM images of single-domain (right) and multidomain (vortex) (left) magnetization states on the vertical nanoislands.

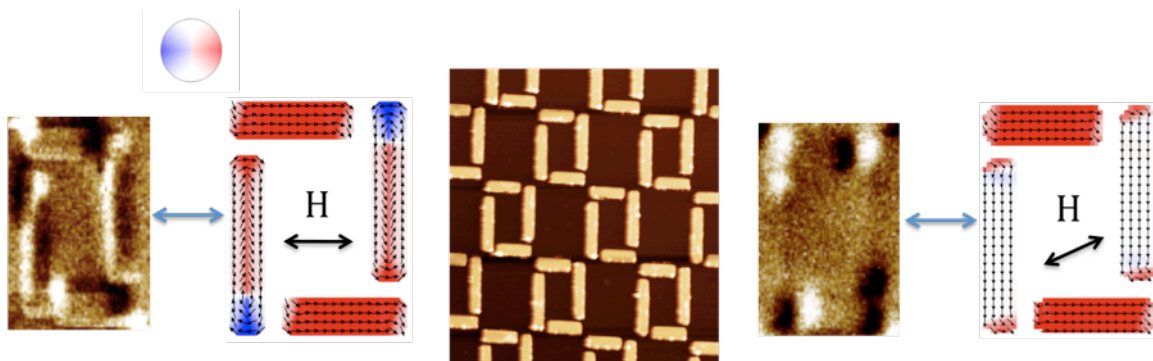


Fig.2: AFM topography image (center) of a checkerboard array of ferromagnetic nanoislands arranged in rectangular units with vertical bars of $1\mu\text{m}$ length ($AR=6$) and horizontal bars of 700nm length ($AR=4$), flanked by micromagnetic simulations and MFM images of single-domain (right) and multidomain (vortex) (left) magnetization states on the vertical nanoislands.

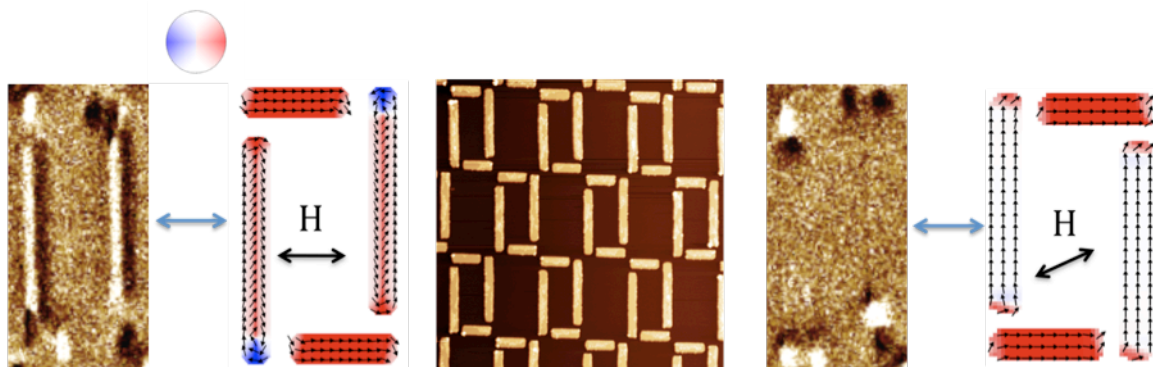


Fig.3: AFM topography image (center) of a checkerboard array of ferromagnetic nanoislands arranged in rectangular units with vertical bars of $1.4\mu\text{m}$ length ($AR=8$) and horizontal bars of 700nm length ($AR=4$), flanked by micromagnetic simulations and MFM images of single-domain (right) and multidomain (vortex) (left) magnetization states on the vertical nanoislands.