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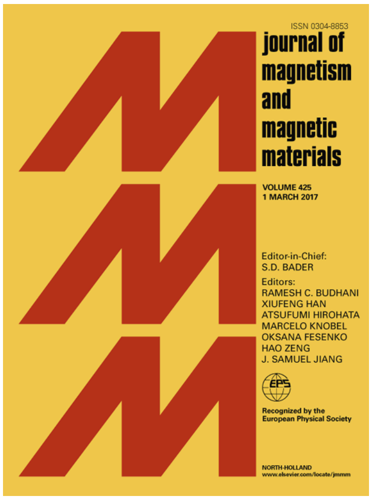

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Spin-ice behavior of three-dimensional inverse opal-like magnetic structures: micromagnetic simulations

I. S. Dubitskiy[a,*], A. V. Syromyatnikov[a,b], N. A. Grigoryeva[b], A. A. Mistonov[a,b], N. A. Sapoletova[c], and S. V. Grigoriev[a,b]

[a]*National Research Center "Kurchatov Institute", Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia*
[b]*Saint Petersburg State University, 7/9 Universitetskaya nab., St. Petersburg, 199034 Russia*
[c]*Lomonosov Moscow State University, Leninskie Gory, Moscow, 119991 Russia*

We perform micromagnetic simulations of the magnetization distribution in inverse opal-like structures (IOLS) made from ferromagnetic materials (nickel and cobalt). It is shown that the unit cell of these complex structures, whose characteristic length is approximately 700 nm, can be divided into a set of structural elements some of which behave like Ising-like objects. A spin-ice behavior of IOLS is observed in a broad range of external magnetic fields. Numerical results describe successfully the experimental hysteresis curves of the magnetization in Ni- and Co-based IOLS. We conclude that ferromagnetic IOLS can be considered as the first realization of three-dimensional artificial spin ice. The problem is discussed of optimal geometrical properties and material characteristics of IOLS for the spin-ice rule fulfillment.

Keywords: artificial spin ice, micromagnetics, inverse opal

I. INTRODUCTION

A focus of interest in the nanomagnetism has shifted in the last decade from the standalone nanoobjects such as cubes [1], disks [2], pyramids [3, 4], hemispheres [5], octahedrons [6], and wires [7] to the ordered arrays of nanoobjects [8, 9] and porous ordered materials [10-12]. It has happened due to rapid progress in the lithographic [13] and self-assembling technologies [14]. One-dimensional (1D) and two-dimensional (2D) nanostructures such as antidot arrays are widely discussed now in magnonics [15-19]. A spin-ice behavior has been realized recently in 2D arrays of magnetic islands by a subtle tuning of system geometry [20, 21]. The latter finding opens a new perspective in discussion related to frustrated magnetic systems.

Possessing a topological phase with the fractional elementary excitations (magnetic monopoles) and macroscopic entropy in the low-temperature limit, spin ices have been intensively studied in recent years [22, 23, 24]. Pyrochlore materials such as $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$ exhibit spin-ice properties caused by two reasons [22]. Firstly, the strong single-ion easy-axis anisotropy forces magnetic moments sitting at vertexes of corner-sharing tetrahedra to be directed to the center of one of the two tetrahedra. Secondly, the interaction between these moments is ferromagnetic. As a result, a frustration arises since ferromagnetic couplings of different moments compete with each other. Such systems are governed at small temperature by the so-called spin-ice rule (proposed initially for the water ice [25]). This rule states that a configuration with the minimal energy is achieved when two magnetic moments are directed into each tetrahedron and two moments are directed out of it (the 2-in-2-out rule). As the number of such states is macroscopically large in the pyrochlore lattice, the ground state is highly degenerate.

Artificial spin ice systems were initially designed to mimic spin-ice pyrochlores [26]. They consist of ordered single-domain ferromagnetic nanoparticles. The Ising-like behavior of magnetic moments of nanoparticles is provided by the shape anisotropy. However it is not easy to achieve the ground state degeneracy caused by the competing interactions in these systems [21, 26].

It was proposed recently that three-dimensional (3D) inverse opal-like structure (IOLS) made from ferromagnetic material can be the first realization of 3D spin-ice system [27]. To interpret the neutron scattering data in the Co-based IOLS, it was suggested that its magnetic behavior is determined mostly by Ising-like magnetic moments situated at vertices of tetrahedra-shaped structural units.

The present paper is aimed to provide a more solid confirmation of the spin-ice behavior of IOLS by studying magnetization distribution using micromagnetic simulations [28]. It is well known that magnetic properties of IOLS depend significantly on their geometry [29, 30, 31, 32]. Then, we restrict ourselves to Co- and Ni-based IOLS described in Refs. [27, 33] whose unit cells have a characteristic length of approximately 700 nm. We find that IOLS can be considered as a three-dimensional network of ferromagnetic nanoobjects (quasicubes and quasitetrahedra) which connect to each other via relatively long and thin crosspieces (“legs”). Due

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[*] Corresponding author.
E-mail address: i.dubitsky@phys.spbu.ru (Ilya Dubitskiy)