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# Magnetic stray-field studies of a single Cobalt nanoelement as a component of the building blocks of artificial square spin ice

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ABSTRACT

We use Focused Electron Beam Deposition (FEBID) to directly write Cobalt magnetic nanoelements onto a micro-Hall magnetometer, which allows for high-sensitivity measurements of the magnetic stray field emanating from the samples. In a previous study [M. Pohlit et al., J. Appl. Phys. 117 (2015) 17C746] [21] we investigated thermal dynamics of an individual building block (nanocluster) of artificial square spin ice. In this work, we compare the results of this structure with interacting elements to the switching of a single nanoisland. By analyzing the survival function of the repeatedly prepared state in a given temperature range, we find thermally activated switching dynamics. A detailed analysis of the hysteresis loop reveals a metastable microstate preceding the overall magnetization reversal of the single nanoelement, also found in micromagnetic simulations. Such internal degrees of freedom may need to be considered, when analyzing the thermal dynamics of larger spin ice configurations on different lattice types.


## 1. Introduction

Due to the advances in nanotechnology fabrication [1] and measurement techniques, single nanoscale magnetic thin film elements are nowadays widely available for both applications and fundamental studies. In recent years, controlling the materials' magnetic properties and the precise arrangement of multiple elements using lithography techniques allowed for studying interaction effects between individual elements in arrays of nanomagnets [2,3]. On the one hand, such interacting arrays of magnetic thin film elements can be utilized to perform complex logic operations making them candidates for future applications in electronic devices [4]. On the other hand, particular structures are successfully employed as geometrically frustrated magnets based on lithographically fabricated single-domain ferromagnetic islands. In the past years, such artificial spin ice systems consisting of large arrays of specifically arranged ferromagnetic nanoislands acting as macroscopic spins with mutual dipolar interactions have become an important research area in nanomagnetism [5,6]. Artificial spin ice structures – due to the ability to access spatially resolved magnetic properties – act as highly tunable two-dimensional model systems for interacting many-body spin systems with frustration [7,8]. Here, the influence of frustration and the emergence of new phenomena like monopole excitations, avalanche effects or chirality can be directly studied for different lattice geometries, interaction strength (*i.e.* inter-island distance) and by reducing the complexity of the system by investigating small numbers or isolated building blocks, see *e.g.* [9–14] and references therein.

While most of these early experiments on collective phenomena arising from competing interactions of individual macrospins on different lattices were performed on large, athermal ensembles with static imaging probes, investigations of the dynamical properties of artificial spin ice have become the focus of more recent studies [15–20].

Along this line of research efforts, we recently established the combination of two new techniques, namely Focused Electron Beam Deposition (FEBID) and micro-Hall magnetometry for fabricating and measuring, individual building blocks of artificial square spin ice [21]. Our study of a single building block of a square spin ice lattice, although consisting of only 12 coupled Co nanoelements, see Fig. 2(a), revealed a rather complex behavior related to the switching between different states of the ensemble during magnetic reversal.

In most of the studies on artificial spin ice structures, it is

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assumed that the magnetic nanoislands behave like macrospins without intrinsic degrees of freedom (microstates), *i.e.* fixed single-domain entities the magnetization of which pointing in one of the two spin directions along their easy axis determined by shape anisotropy. In this simplified picture, transitions between distinct states of the lattice are described by flipping over one or more elements in a process that is idealized to be instantaneous. Nevertheless, intrinsic microstates are not uncommon in nanoelements of dimensions typical for the macrospins in spin ice structures, and if present they may affect the reversal processes or influence the coupling interactions at the lattice nodes. Therefore, such internal degrees of freedom are sought to be avoided during sample preparation by carefully choosing suitable geometries (if possible), or they need to be taken into consideration in the demagnetization protocols and entropy considerations of the underlying lattice. In this work, we aim to examine the general assumption that the nanoislands of the previously studied spin ice nanocluster [21] can be simplified as interacting macrospins with two idealized magnetization configurations (orientations). This question is addressed by investigating a single Co nanoelement fabricated by FEBID on a micro-Hall sensor, *i.e.* an elementary building element of the previously investigated square-lattice nanocluster. The magnetic measurements are supported by micromagnetic simulations using the OOMMF package [22].

## 2. Material and methods

For this experiment, the magnetic sample is directly deposited on a Hall sensor for magnetic stray field measurements. The combination of FEBID and micro-Hall magnetometry allows for high-resolution detection of switching processes of individual nanoscale magnetic samples deposited in a direct writing process, *i.e.* without further lithography steps.

### *2.1. Sample fabrication using Focused Electron Beam Induced Deposition (FEBID)*

The isolated Cobalt-based nanomagnet was prepared using FEBID, where the organo-metallic precursor gas $Co_2(CO)_8$ is decomposed in the focus of an electron beam [23–25]. The rather complex deposition process, which is schematically depicted and described in Fig. 1(a), requires process parameters which can be optimized and tuned to alter the physical (magnetic) properties of the deposit as compared to the associated metal. Recently, using this technique high quality Cobalt-based ferromagnetic nanostructures with high lateral resolution (below 30 nm) and metal contents of up to 95% were grown [26,27]. For such Co nanowires a metallic temperature dependence of the resistivity and values of the saturation magnetization of $M_s = 1329 \pm 20$ kA/m close to the bulk value have been found [26]. In the present case, the geometry and process parameters of the Co nanoelement were chosen similar to our previously studied spin ice nanocluster [21] with nominal dimensions (as written by the SEM) of $250 \times 50 \times \sim 15\,\text{nm}^3$ using a beam energy of 3 keV and beam current of 33 pA. Note that the crystal structure and grain size of the deposited material depend on the chosen beam parameters and in particular vary with the employed beam current (for details see [28,29]). In our case, *i.e.* for small beam currents, a mixture of hcp/fcc Cobalt with crystal size of 2–5 nm is expected (see [30], where a deposit with beam parameters close to the ones employed here was studied).

### *2.2. Stray-field detection using micro-Hall magnetometry*

The individual magnetic nanostructures were investigated using micro-Hall magnetometers that have proven to be versatile tools allowing for high-precision measurements of the local magnetic induction in a wide temperature and field range [31], while the sensor surface can be directly used as substrate for sample preparation [21]. The homebuilt micro-Hall sensor was fabricated from a high-mobility two-dimensional electron gas (2DEG) based on a GaAs/AlGaAs heterostructure. For optimizing magnetic measurements, the Hall sensors are characterized regarding their intrinsic noise properties [32]. Using electron beam lithography followed by wet chemical etching, six adjacent Hall crosses (active area of $1 \times 1\,\mu\text{m}^2$) were formed. The 2DEG is electronically contacted by annealed AuGe/Ni contacts and the sensor is covered by a thin gold top-gate. The basic principle of operation is schematically shown in Fig. 1(b) with the sample positioned ontop of the gold gate covering the sensor structure while its emanating stray field, which is determined by the sample's state of magnetization, penetrates the 2DEG. The electronic read out of the sensor is performed using standard lock-in techniques measuring the Hall voltage $V_H$ induced by the perpendicular component of the sample's stray field $\langle B_z \rangle$ averaged over the active area of the Hall cross, $R_H = V_H/I = 1/ne \cdot \langle B_z \rangle$, where $I$ denotes the applied current and $n = 2.5 \times 10^{11}\,\text{cm}^{-2}$ the carrier concentration at low temperatures. An external magnetic field parallel to the sensor plane was applied in order to manipulate the sample's magnetization. Note that in this geometry the external field has no perpendicular component onto the device and therefore only the signal from the

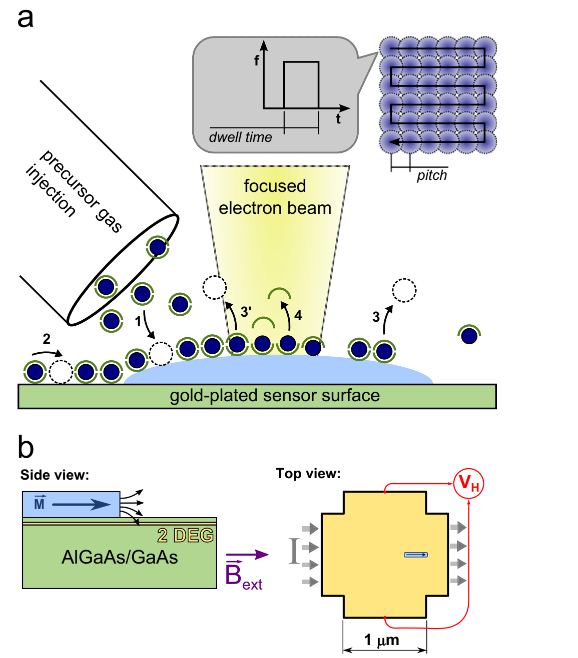


**Fig. 1.** (a) Illustration of the sample preparation using focused Electron Beam Induced Deposition (FEBID). The organo-metallic precursor molecules (blue: metal, green: organic ligands) are supplied by a gas-injection system and physisorb (1) on the surface. On the surface diffusion (2), thermally induced desorption (3) and electron-stimulated desorption (3') take place. Within the focus of the electron beam, adsorbed precursor molecules are (partly) dissociated followed by desorption of volatile organic ligands (4). Upper right: for pattern definition the electron beam is moved in a raster fashion (here: serpentine) over the surface and settles on each dwell point for a specified dwell time. After one raster sequence is completed the process is repeated until a predefined number of repeated loops is reached (after [23]). (b) Schematic view of the magnetic stray-field measurement setup using micro-Hall magnetometry. The perpendicular component of the sample's stray field, which is determined by its magnetization state, is measured by detecting the generated Hall voltage ($V_H$) in the sensor plane using standard Lock-In techniques. An external magnetic field is applied parallel to the sensor plane in order to manipulate the sample's magnetization. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)