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Research articles

Prevalence of information stored in arrays of magnetic nanowires against external fields

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ABSTRACT

Arrays of magnetic nanowires in porous alumina can be used to store information inscribed on the system by orienting the magnetization of selected wires pointing in a desired direction, so symbols can be read as ferromagnetic sectors. However, this information is subject to aging and the stored information could be gradually lost. We investigate here two mechanisms proposed to improve the prevalence of the stored information: opposite ferromagnetic band at the center of the symbol and bi-segmented nanowires acting as two layers of nanowires storing the same information. Both mechanisms prove to increase resistance to the action of external magnetic fields for the case of Ni wires in a geometry compatible with actually grown nanowires. Advantages and disadvantages of these mechanisms are discussed.

1. Introduction

Arrays of magnetic nanowires trapped in alumina membranes [1–7] or grown on silicon substrates [8] provide alternative ways to store information such as security codes, firmware [9] or bar codes [10]. However, the stored information can gradually fade away due to magnetization reversal of individual nanowires [3,11–14]. To avoid this aging phenomenon, two stabilization mechanisms for the stored information have been proposed: the inscription of an opposite ferromagnetic band (OFB) within the symbols storing information [9], and the multiplication of the stored information in the layers formed by multisegmented magnetic nanowires [15,16]. Both techniques minimize the repulsive magnetostatic energy among wires in the symbol, thus reducing the probability of triggering magnetization reversals. The advantages of the former relay on the low costs it requires, while the advantages of the latter are the higher possibility of recovering information in a partially damaged device; these aspects will be discussed below.

The effect of an external magnetic field for these two preservation methods has not been considered so far. This is important since stored information can be exposed to unexpected magnetic fields coming from different sources such as tools, gadgets, toys and even natural sources such as lightening or cosmic radiation. In the present paper we explore the robustness of previously mentioned methods in the presence of external magnetic fields. This also explores the way in which the information is gradually lost and the possibilities of recovery. In the case of multisegmented wires, we have focused in those having two equivalent magnetic segments at the ends, which are separated by a non-magnetic spacer, namely bi-segmented magnetic nanowires.

We have organized this paper as follows: in Section II we present the theoretical model, describing the system under study and the methodology. Section III contains the results and discussion for both stabilization mechanisms, and finally Section IV is devoted to main conclusions.

2. Theoretical model

2.1. System

Following to the geometries obtained after the synthetization procedures [1,2,6,17], our system is formed by magnetic nanowires (homogeneous or bi-segmented) ordered in a triangular array. Without lost of generality, we can consider identical cylindrical wires of radius b and lenghth $2L$ (See Fig. 1(a)). Such definition for wires length allows us to maintain algebraic expressions already derived [9,15,16,18]. For bi-segmeted wires it is also necessary to consider the longitudinal separation t between the magnetic segments forming a wire. Noteworthy, this same parameter defines the separation between the two layers of magnetic segments that appears when the bi-segmented nanowires are forming

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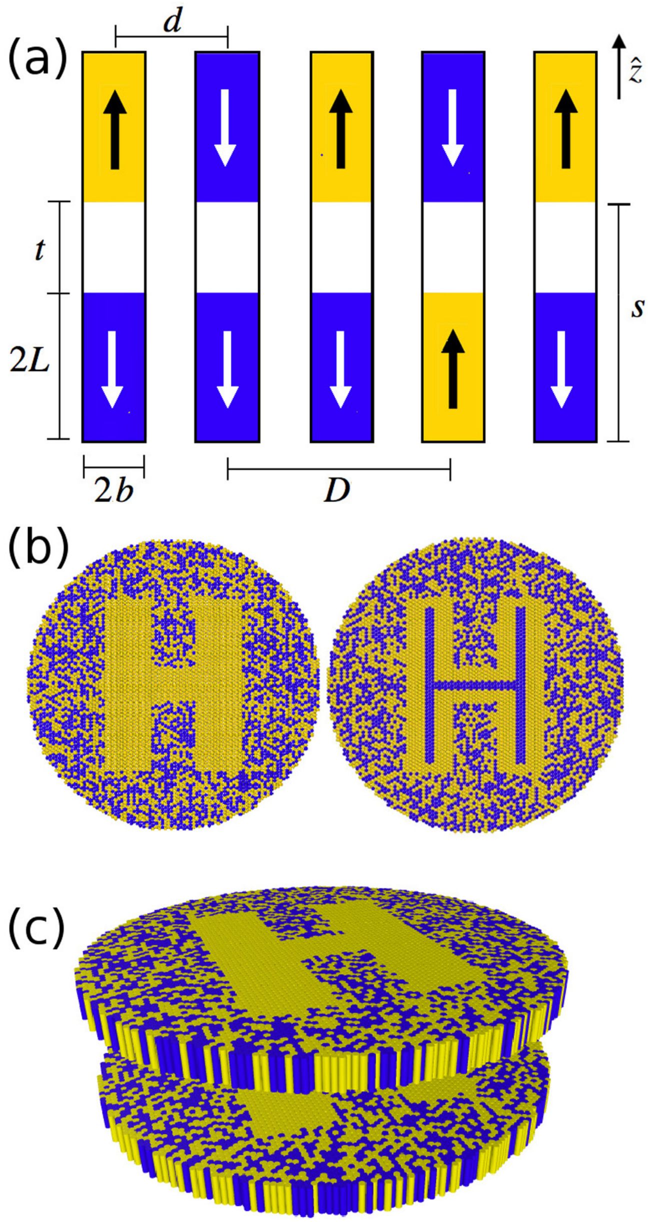

Fig. 1. (a) Side view of a group of bi-segmented magnetic nanowires ordered inside the membrane used to synthesize them. They present an uniform axial magnetization pointing up (yellow) or down (blue). (b) Top view of circular membranes where ferromagnetic patterns forming the letter H have been inscribed with (right) and without (left) an opposite ferromagnetic band as a stabilization mechanism. (c) Schematic view for the inscription of a ferromagnetic pattern within a circular membrane containing bi-segmented magnetic nanowires; the two resulting layers are clearly presented. The case of a membrane holding homogeneous magnetic nanowires is equivalent to one of these layers with the appropriate changes in the geometrical parameters.

an array (See Fig. 1(c)). In the case of homogeneous wires, the system maintains the same cylinder distribution and it is equivalent to a single layer of wires. Nevertheless, it is convenient for the mathematical treatment to define $s = 2L + t$ as the vertical displacement for nanowires belonging to different layers.

Due to the shape anisotropy [19], the magnetization of each wire is mostly oriented along its axis and points in any of the two possible directions. An arbitrary color code was adopted to identify such magnetization orientations within an array of magnetic nanowires: yellow for upward direction and blue for downward direction (See Fig. 1). In the case of an as grown array of nanowires, the total magnetization tends to cancel minimizing in this way the local magnetic energy. This can be achieved when individual wires orient at random their corresponding magnetization senses [20,21]. A quenching mechanism was studied but not noticeable differences appear with respect to random backgrounds. As proposed before [15,16], information can be stored as ferromagnetic symbols, letters [21] or bar codes [10]. The left-hand side of Fig. 1(b) illustrates this idea, where the letter H has been inscribed within a circular membrane holding an array of magnetic nanowires. We have chosen here letters spanning a large portion of the circular membrane under study; the case of the letter H is also important due to its three elements with two connecting points [22].

As stated before, magnetization reversal [11–14] can affect the stored information, so two stabilization mechanisms have been recently proposed: the inscription of an opposite ferromagnetic band (OFB) [9,16] and the employment of multisegmented magnetic nanowires [15]. The right-hand side of Fig. 1(b) and Fig. 1(c) [23] schematize these stabilization mechanisms. In the case of an OFB, the optimal width is about 1/3 of the band defining the symbol [22].

In what follows, we consider wires of total length 12,000 nm and external radius $b = 25$ nm, while $d = 100$ nm corresponds to the lattice constant of the triangular array. All these parameters correspond to realistic geometrical characteristics taken from the literature [20,24]. In addition, and for practical purposes, we consider a circular membrane of radius $R = 4$ μm containing 6067 Ni nanowires for inscribing symbols one at a time and studying their prevalence as external magnetic fields may approach them. The magnetization saturation for Ni was taken as $M_{sat} = 480$ emu cm^{-3}, while a 730 Oe coercitive field [20,25] was considered for homogeneous wires.

2.2. Methodology

The mathematical treatment for the interaction energy between two magnetic objects of arbitrary shape [26] were particularized by Escrig et al. for two parallel tubes having uniform axial magnetization [27]. However, the resulting expression involves integration over Bessel functions which need time consuming techniques from a computational point of view. This is even more noticeable in the present case where a huge number of magnetostatic interactions need to be evaluated. Nevertheless, for wires having a high aspect ratio ($b \ll 2L$), the magnetostatic interaction between two magnetic nanowires, $E(i,j)$, can be reduced to the following algebraic form [15,16,18]:

$$E^{(i,j)} = \sigma_i \sigma_j \frac{b^2}{8L}\left[\eta_0 + \eta_2 b^2 + 5\eta_4 b^4\right], \tag{1}$$

where σ_i takes the value ± 1 to reflect the magnetization orientation of each cylinder. The functions η_i are given by simple algebraic expressions in terms of d, L and s:

$$\eta_0 = \frac{2}{\sqrt{D^2+s^2}} - \frac{1}{\sqrt{D^2+s_+^2}} - \frac{1}{\sqrt{D^2+s_-^2}}, \tag{2}$$

$$\eta_2 = \frac{D^2-2s^2}{2(D^2+s^2)^{5/2}} - \frac{D^2-2s_+^2}{4(D^2+s_+^2)^{5/2}} - \frac{D^2-2s_-^2}{4(D^2+s_-^2)^{5/2}}, \tag{3}$$

$$\eta_4 = \frac{3D^4 - s^2D^2 + 8s^4}{32(D^2+s^2)^{9/2}} - \frac{3D^4 - 24D^2s_+^2 + 8s_+^4}{64(D^2+s_+^2)^{9/2}} - \frac{3D^4 - 24D^2s_-^2 + 8s_-^4}{64(D^2+s_-^2)^{9/2}}. \tag{4}$$