Journal of Magnetism and Magnetic Materials 324 (2012) 2360–2362

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Angular dependence of the coercivity and remanence of ordered arrays of Co nanowires

R. Lavín [a,b], C. Gallardo [a], J.L. Palma [a], J. Escrig [a,c], J.C. Denardin [a,c,*]

[a] Departamento de Física, Universidad de Santiago de Chile, USACH, Av. Ecuador 3493, Santiago, Chile
[b] Facultad de Ingeniería, Universidad Diego Portales, UDP, Ejército 441, Santiago, Chile
[c] Center for the Development of Nanoscience and Nanotechnology, CEDENNA, Av. Ecuador 3493, Santiago, Chile

ARTICLE INFO

Article history:
Received 6 September 2011
Received in revised form
5 February 2012
Available online 9 March 2012

Keywords:
Coercivity and remanence
Magnetization reversal
Magnetic nanowire

ABSTRACT

The angular dependence of the coercivity and remanence of ordered hexagonal arrays of Co nanowires prepared using anodic aluminum oxide templates was investigated. The experimental evolution of coercivity as a function of the angle, in which the external field is applied, is interpreted considering micromagnetic simulations. Depending on the angle between the axis of the wire and the applied magnetic field direction our results show that the magnetization reversal mode changes from vortex to a transverse domain wall. Besides, we observed that the dipolar interactions cause a reduction in coercive fields, mainly in the direction of easy magnetization of the nanowires. Good agreement between numerical and experimental data is obtained.

1. Introduction

The magnetic nanostructures that exhibit a high uniaxial anisotropy can be an alternative to overcome the superparamagnetic limit. This limit appears in small magnetic particles on the order of nanometers [1]. An alternative is to use magnetic nanowires. Its simple geometry and high aspect ratio can be regarded as a model for the study of uniaxial nanoparticles. Lithographic techniques can be used to grow magnetic nanowires, however, this technique is very expensive and time consuming. An alternative is to use chemical template-based methods combined with high-yield electrochemical deposition techniques. A widespread example is anodic aluminum oxide (AAO) membranes, which stand as a quite versatile and nearly inexpensive technique to fabricate arrays with reproducible properties. Ordered arrays of magnetic nanowires are of great interest for high-density data storage devices [2,3], Magnetic Random Access Memory (MRAM) and other electronic devices [4,5], biomedical applications [6], optical applications [7], and magnetic sensors based on magnetoresistance [8,9]. Cobalt nanowires form a particularly interesting system as it is a relatively hard magnetic material whose magnetic properties can be tailored through the variation of the geometry [10] and of the structural parameters derived form crystallinity [11,12].

The magnetic properties (coercivity and remanence) of the nanowires are determined by the process of magnetization reversal, that is, the change of magnetization from one of its minimal energy states to the other [13–15]. These modes are known as coherent rotation (C), in which all the spins simultaneously rotate, transverse (T) and vortex (V) reversal modes, in which the spins progressively invert through the propagation of a transverse and vortex domain wall. The applicability of any mode depends on the geometrical characteristics. Since coercivity is directly related to the reversal mechanism, we can induce different reversal modes by modifying external parameters, such as the direction of the applied field. Then, a previous work [16,17] presented an analytical model that describes the angular behavior of the coercivity, H_c. However, this analytical model is not capable of including the effect of the dipolar interactions among nanowires. Thus, it is necessary to realize micromagnetic simulations in order to investigate how the interactions modify the angular dependence of the coercivity and remanence in Co nanowire arrays.

Thus, the study of the angular dependence of coercivity is a successful tool to unveil the reversal mechanism in ordered arrays of Co nanowires. Different reversal modes can be induced by suitable modification of the angle in which the external field is applied.

2. Experimental details

Our approach to the preparation of magnetic Co nanowires arranged in hexagonally ordered, parallel arrays is based on the

* Corresponding author at: Departamento de Física, Universidad de Santiago de Chile, USACH, Center for the Development of Nanoscience and Nanotechnology, Av. Ecuador 3493, Santiago, Chile. Tel.: +56 2 7181256.
E-mail addresses: jcdenardin@gmail.com, juliano.denardin@usach.cl (J.C. Denardin).

0304-8853/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2012.02.125

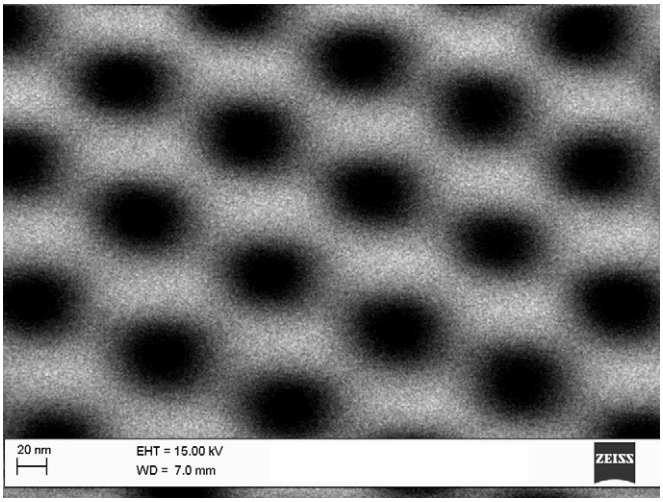

Fig. 1. SEM image of the surface of an anodic aluminum oxide membrane used for the electrodeposition.

combination of two complementary aspects, namely (i) the use of self-ordered anodic aluminum oxide (AAO) as a porous template and (ii) the electrodeposition of magnetic material in the cylindrical pores [18]. A Zeiss EVO MA 10 apparatus was used for scanning electron microscopy (SEM) measurements. Fig. 1 shows a SEM image of the membrane used for the electrodeposition of magnetic material, showing that these present highly ordered pores of diameter $d=50$ nm and lattice constant $D=100$ nm. The nanowires are 4 μm long. We have measured hysteresis curves of Co nanowire arrays at 300 K by a vibrating sample magnetometer (VSM). The samples are rotated in relation to the magnetic field direction allowing probing the dependence of the coercive field and remanence with the angle ($\boldsymbol{\theta}$) between the field and the long axis of the wires.

3. Micromagnetic simulation

In order to investigate the angular dependence of coercivity and remanence in an interacting array, we performed micromagnetic simulations using the 3D OOMMF package [19]. The method to solve the magnetic behavior of a magnetic sample in time is carried out by implementing a first order forward Euler method with step size control on the Landau–Lifshitz ordinary differential equation. The magnetization of the sample is computed as a function of time using the damped Landau–Lifshitz–Gilbert equation of motion (LLG) of magnetization at zero temperature [20]. Our starting point is a hexagonal cell of 7 nanowires characterized by a length of 1 μm, a diameter of 50 nm and a separation between them of 100 nm. We have used a length of 1 μm instead of 4 μm to reduce the simulation time. Despite this, the results of the simulations are representative because the aspect ratio of the wires is large enough. Thus, the ferromagnetic system is spatially divided into cubic cells and within each cell the magnetization is assumed to be uniform. The micromagnetic simulations are performed using typical Co parameters: saturation magnetization $M_0=1.4\times10^6$ A/m, exchange stiffness constant $A=30\times10^{-12}$ J/m. Effects of discretization are inherent to the methodology used here. For this reason we have investigated the effects of the cell size and found that for cells smaller than $5\times5\times5$ nm^3 the results are size independent. For most of our simulations we consider cell sizes of $2\times2\times5$ nm^3, where spins are free to rotate in three dimensions. In all the cases the damping parameter was chosen as 0.5. In order to understand the behavior of the magnetostatic interactions between the nanowires, we also have simulated an isolated wire, under the same conditions as described previously.

4. Results and discussion

Fig. 2 shows the coercivity measured at different angles for the Co nanowire arrays. Dots and solid lines represent the coercivity obtained by means of experimental measurements and micromagnetic simulations, respectively. We observed a non-hysteretic behavior for $\theta=90^\circ$. This behavior allows us to conclude that shape anisotropy of nanowires may induce a hard axis of magnetization when $\theta=90^\circ$. Besides, for the Co nanowire array we can observe a transition from a vortex (V) to a transverse (T) reversal mode as a function of θ.

If we compare our numerical results obtained for an isolated wire with the results obtained for an array of seven nanowires we can see the effect of the dipolar interactions among them. Fig. 2 shows that the effect of dipolar interactions between nanowires reduces the coercivity for all the angles considered. However, the effect of interactions between Co nanowires strongly modified the value of the coercive field for $\theta=60^\circ$. This indicates that the dipolar interaction among the Co wires is much stronger when the external field is applied in the direction of easy magnetization of the nanowires. Finally, it is worth to note the good agreement between experimental data points and micromagnetic simulations for interacting arrays. Small differences of the experimental data points from the calculated ones likely originate from the number of nanowires considered in our simulations. Other factors not accounted for in our numerical simulations include possible shape irregularities and the real length of the nanowires.

Fig. 3 shows the angular dependence of remanence, M_r/M_0, as a function of θ for the Co nanowire array. The magnetization of each nanowire in an array is oriented parallel to the axis of the wires, owing to the shape anisotropy. When the applied field is reduced to zero, at remanence, the magnetization of each nanowire is along its axial axis, but the magnetization is measured at the θ angle with respect to the easy axis. Thus, we can observe that the remanence follows the function, $M_r(\theta)=M_r\cos^2(\theta)$, independent of the number of nanowires, with $M_r=M_r(\theta=0)$ the remanence measured at $\theta=0$. This behavior is an indication that long nanowires follow the behavior of the uniaxial systems.

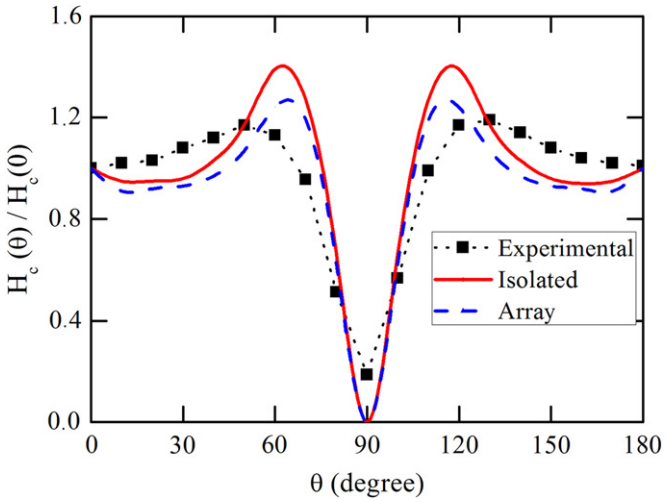

Fig. 2. Angular dependence of coercivity for the Co nanowire arrays. Dots correspond to the experimental data, solid line to the results obtained with the simulation considering an isolated nanowire, and dashed line to the simulation considering an hexagonal array of 7 nanowires.

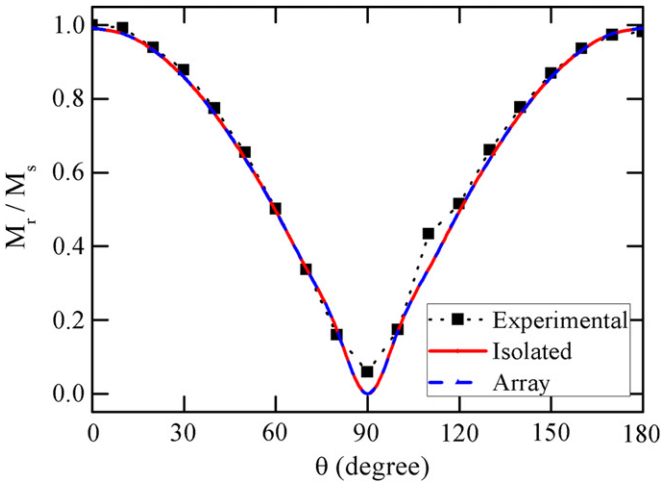

Fig. 3. Angular dependence of remanence for the Co nanowire arrays. Dots correspond to the experimental data, solid line to the results obtained with the simulation considering an isolated nanowire, and dashed line to the simulation considering an hexagonal array of 7 nanowires.

In conclusion, by means of experimental techniques and micromagnetic simulations we have investigated the angular dependence of the reversal modes in ordered arrays of Co nanowires. Besides, we observed that the dipolar interactions directly translate into a reduction in coercive fields, which is the strongest in the direction of easy magnetization of the nanowires. Good agreement between numerical and experimental data is obtained.

Acknowledgments

The authors acknowledge financial support from the FONDECYT Grants 3100117, 1110784 and 1110252, Grant ICM P10-061-F by the Fondo de Innovación para la Competitividad-MINECON, AFOSR FA9550-11-1-0347 and the Financiamiento Basal para Centros Científicos y Tecnológicos de Excelencia, under Project FB0807.

References

[1] S. Sun, C.B. Murray, D. Weller, L. Folks, A. Moser, Science 287 (2000) 1989.
[2] K. Nielsch, R.B. Wehrspohn, J. Barthel, J. Kirschner, U. Gösele, S.F. Fischer, H. Kronmüller, Applied Physics Letters 79 (2001) 1360.
[3] C.A. Ross, M. Hwang, M. Shima, H.I. Smith, M. Farhoud, T.A. Savas, W. Schwarzacher, J. Parrochon, W. Escoffier, H.N. Bertram, F.B. Humphrey, M. Redjdal, Journal of Magnetism and Magnetic Materials 249 (2002) 200–207.
[4] R.P. Cowburn, D.K. Koltsov, A.O. Adeyeye, M.E. Welland, D.M. Tricker, Physical Review Letters 83 (1999) 1042–1045.
[5] Th. Gerrits, H.A.M. van den Berg, J. Hohlfeld, L. Bär, Th. Rasing, Nature 418 (2002) 509–512.
[6] A. Prina-Mello, Z. Diao, J.M.D. Coey, Journal of Nanobiotechnology 4 (2006) 9.
[7] M. Tanase, L.A. Bauer, A. Hultgren, D.M. Silevitch, L. Sun, D.H. Reich, P.C. Searson, G.J. Meyer, Nano Letters 1 (2001) 155–158.
[8] K. Liu, C.L. Chien, P.C. Searson, K.Yu Zhang, Applied Physics Letters 73 (1998) 1436.
[9] J. Heremans, C.M. Thrush, Y.-M. Ling, S. Cronin, Z. Zhang, M.S. Dresselhaus, J.F. Mansfield, Physical Review B 61 (2000) 2921.
[10] L.G. Vivas, R. Yanes, O. Chubykalo-Fesenko, M. Vazquez, Applied Physics Letters 98 (2011) 232507.
[11] M. Vazquez, L.G. Vivas, Physica Status Solidi B 248 (2011) 2368.
[12] L.G. Vivas, M. Vazquez, J. Escrig, S. Allende, D. Altbir, D.C. Leitao, J.P. Araujo, Physical Review B 85 (2012) 035439.
[13] R. Hertel, Journal of Magnetism and Magnetic Materials 249 (2002) 251.
[14] H. Forster, T. Schrefl, W. Scholz, D. Suess, V.D. Tsiantos, J. Fidler, Journal of Magnetism and Magnetic Materials 249 (2002) 181.
[15] P. Landeros, S. Allende, J. Escrig, E. Salcedo, D. Altbir, E.E. Vogel, Applied Physics Letters 90 (2007) 102501.
[16] R. Lavín, J.C. Denardin, J. Escrig, D. Altbir, A. Cortés, H. Gómez, Journal of Applied Physics 106 (2009) 103903.
[17] R. Lavín, J.C. Denardin, A.P. Espejo, A. Cortés, H. Gómez, Journal of Applied Physics 107 (2010) 09B504.
[18] J. Escrig, R. Lavín, J.L. Palma, J.C. Denardin, D. Altbir, A. Cortés, H. Gómez, Nanotechnology 19 (2008) 075713.
[19] M.K. Donahue, D.G. Porter, OOMMF User's Guide Version *1.2a3* (2002). 〈http://math.nist.gov/oommf〉.
[20] T.L. Gilbert, Physical Review 100 (1955) 1243.