Box Model for Hysteresis Loops of Arrays of Ni Nanowires

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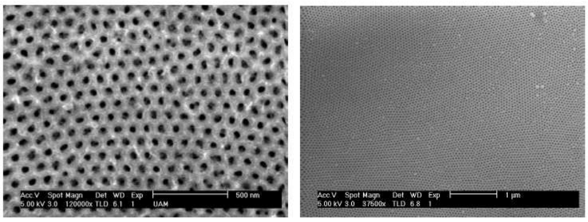
In the present work, by means of a phenomenological model, we simulate the hysteresis loop of an hexagonal array of Ni nanowires. Our model is based on the assumption that the hysteresis loop of a single wire is a rectangular box with a particular value of the coercive field, and the effect of the array is to generate a distribution of the coercive fields. Our results are in good agreement with experimental data.

Keywords: Nanowires; Hysteresis; Phenomenological model

I. INTRODUCTION

During the last decade, arrays of nanowires have been extensively studied. Particular properties arising from the intrinsic nature of the nanowires together with the magnetic ordering of the array give rise to outstanding properties of fundamental and technological interest in areas such as semiconductors, magneto-optics, biomedical and magnetic storage [1–2]. Different procedures can be used to fabricate nanowires arrays [3–4]. In general, the first step is a careful production of nanoporous alumina membranes, with the highest quality and well controlled geometrical characteristics. Nanoporous alumina membranes with hexagonal ordering have been prepared by a two-step anodisation process; after that the nanoporous are filled with Ni by electro deposition. Fig. 1 illustrates a nonporous and Ni nanowires array pattern.



(a) (b)

FIG. 1: a) Surface image obtained by means of FMF (Magnetic Force Microscope) of an array of nanopores. b)The same nanoporus array filled with Ni.

From the theoretical point of view, many different studies of the hysteresis loop of nanowires arrays have been presented in the literature. We can mention some works based on methods using the Anhysteretic curve [5], statistical approaches via Monte Carlo simulations [6] or micro-magnetic calculations [7]. However, analytical calculations have not been developed yet.

The aim of this paper is to simulate the hysteresis loop using a simple phenomenological model basede on the assumption that the hysteresis loop of each wire has the form of a rectangular box with a particular coercive field. The effect of the array can be described by the inclusion of a distribution of the coercive fields. This method has three important strenghtens; first the two assumptions are based on experimental evidence; second, it takes into account the intrinsic non-irreversible character of the hysteresis, and finally it gives an analytical description of the loop. The paper is organized as follows. In Sec. II, the model is presented and the hysteresis loop of a Ni nanowire array is obtained. Finally, conclusions are presented in Sec. III.

II. MODEL AND RESULTS

Not much about the magnetization processes occurring in an array of closely packed magnetic nanowires are known. This happens because even single nanowires may have internal complex magnetic structures, closure domain structures at the edges, etc [8]. The problem becomes even more complicated when the long-range magnetostatic coupling between nanowires is considered. Therefore the modelling of these systems is often subject to strong simplifications. For example, magnetostatic interactions between wires are sometimes investigated by assuming that each nanowire can be regarded as a single monodomain which is described as a big dipole [6,9]. Though many of the models based on simplifying assumptions yield often good agreement with experimental observation, their validity is sometimes discussed. For nanowires with diameters of less than 60 nm it is reasonable to expect that a single nanowire can behave like a monodomain. In this work we investigate the properties of such an array. Therefore, for modelling the hysteresis loop we do not consider the internal domain structure [7] of the magnetization along the wire. Then, a single wire has only two possible magnetic states with its magnetic moment pointing up or down. Within this model we assume that the loop of each single nanowire has a rectangular form with a particular value of the anisotropy field. We consider the following simple mathematical function to describe each part of the loop of a single wire

$$M_{one}(x) = m(2\Theta(x) - 1) \quad , \tag{1}$$

where $\Theta(\bullet)$ is the Heaviside Step distribution and m is the magnetic moment of a single wire, so the total loop is given by

$$M_{one}\left(H+H_a\right)\cup M_{one}\left(H-H_a\right), \tag{2}$$

with H_a the coercive field. Equation (2) represents a square hysteresis loop, which is typical of bi-stable systems and hard magnetic materials.

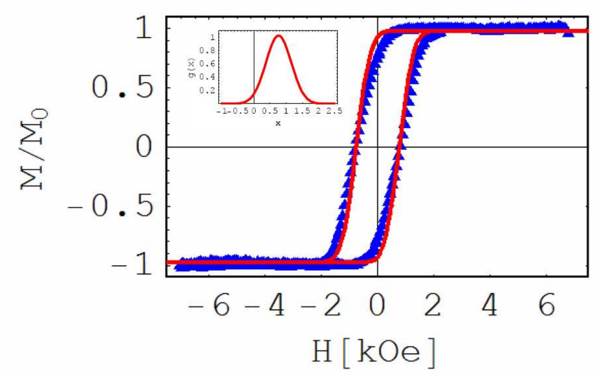


FIG. 2: Solid line: Hysteresis cycle obtained using the rectangular box model for a single nanowire with a distribution of coercive fields. Triangles: experimental data. The inset shows the distribution of anisotropy field obtained by fitting the model with the experimental result.

Our model also considers that the anisotropy field varies from one wire to other so the array shows a distribution of anisotropy fields, giving rise to a distribution of coercive fields. We assume that the coercive field of the array follows a normal distribution, defined by

$$g\left(x\right)=\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\left(x-\mu\right)^2\Big/2\sigma^2\right), \tag{3}$$

where σ and μ are constants. Then the collective effect at each part of the loop can be express in the form

$$M^{\mp}_{Tot}\left(H\right)=N^{-1}\int M_{one}\left(H\pm\xi\right)g\left(\xi\right)d\xi, \tag{4}$$

where the super index + or - depicts the upper or lower branch of the cycle and N corresponds to a normalization constant. In addition, equation (4) can be express in a close form

$$aM^{\mp}_{Tot}\left(H,\xi,\sigma\right)=\sqrt{2\pi}\sigma Erf\left(\left(x\pm\mu\right)\Big/\left(\sqrt{2}\sigma\right)\right), \tag{5}$$

where $Erf\left(\bullet\right)$ is the error function. Fig. 2 illustrates the hysteresis loop generate by equation (5). The best fit of the experimental data illustrated also in Figure 2 is obtained with $\sigma=0.6886$ and $\mu=-0.37382$.

We observe that our results are in good agreement with the experimental data. In addition we remark that the best distribution function of the coercive field has a negative shift. The reason for the appearance of this component is the in-plane anisotropy originated in the dipolar interaction between the wires. Then our model also considers the effect of magnetostatic interactions between the array.

III. CONCLUSION

We have presented an analytical and simple model to describe the hysteresis loop of magnetic nanowire arrays. Our model considers each wire as a big magnetic moment with two possible states which changes under the influence of an external magnetic field parallel to it. The effect of the array arises in the distribution of the coercive field considered. This simple model describes quantitatively well the shape of the magnetization curve for nanowire arrays of less than 60 nm. diameter.

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[1] C. Lapointe, A. Hultgren, D. M. Silevitch, E. J. Felton, D. H. Reich, and R. L. Leheny, Science, **303**, 652 (2004).
[2] Y. Wu, J. Xiang, C. Yang, W. Lu, and C. M. Lieber, Nature **430**, 61 (2004).
[3] H. Masuda, K. Fukuda, Science, **268**, 1466 (1995).
[4] R.M. Metzger, V. V. Konovalov, M. Sun, T. Xu , G. Zangari, B. Xu, M. Benakli, and W. D. Doyle, IEEE Trans. Magn., 36, 30 (2000).
[5] P. Allia, F. Ghigo, M. Knobel, P. Tiberto, and F. Vinai, J. Mag. Mag. Mat., **158**, 319 (1996).
[6] M. Vazquez, K. Nielsch, P Vargas, J. Velazquez, D. Navas, K. Pirota, M. Hernandez-Velez, E. Vogel, J. Cartes, R.B. Wehrspohn, and U. Gosele, Physica B, **343**, 395 (2004).
[7] R. Hertel, J. Magn. Magn. Mater **249**, 251 (2002).
[8] L. Belliard, J. Miltat, A. Thiaville, S. Dubois, J. L. Duvail, and L. Piraux, J. Magn. Magn. Mater **19**0, 1 (1998).
[9] J. Velazquez, C. Garcia, M. Vazquez, and A. Hernando, J. Appl. Phys. **85**, 2768 (1999).