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I Astefanoaei

I Dumitru

A Diaconu

L Spinu
University of New Orleans

A Stancu

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The temperature dependence of hysteretic processes in Co nanowires arrays

I. Astefanoaei,[1,a)] I. Dumitru,[1] A. Diaconu,[1] L. Spinu,[2] and A. Stancu[1]
[1]*Department of Solid State and Theoretical Physics, Al. I. Cuza University, 500706 Iasi, Romania*
[2]*Advanced Materials Research Institute (AMRI), University of New Orleans, New Orleans, Louisiana 70148, USA*

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In this paper, the temperature dependence of the hysteretic processes of Co nanowires, squarelly ordered in an array prepared by electrodeposition in nanopores of alumina membranes was analyzed. Both the magnetostatic interactions induced in the nanowires arrays and the thermal stresses (radial, azimuthal and axial stresses), which appear during the cooling of the system (nanowire and alumina template) from room temperature to 3 K was evaluated. The analysis of thermal induced stresses provides useful informations concerning the magnetic anisotropy in the Co nanowires. The temperature dependence of the remanent magnetization and coercitive field as an effect of the induced thermal stresses and magnetostatic interactions between nanowires was studied. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2837500]

I. INTRODUCTION

The magnetic nanowire arrays have important potential technological applications as magnetic recording media, nanosensors, and magnetodielectrics for microwave devices.[1–5] The study of hysteretic processes in nanowire arrays is receiving a considerable experimental and theoretical attention due to the necessity of understanding the magnetization processes of these magnetic systems.[6] In this paper, we have analyzed the following important tasks:

(i) The thermal stresses during the cooling process from room temperature to 3 K. The thermal stresses were calculated, which appear both due to the cooling (because of the thermal gradients) and to the constraints produced on the nanowire by the alumina template as a result of the difference between the thermal expansion coefficients of the two materials in contact. Using the distribution of internal stresses, the magnetoelastic anisotropy field of nanowires in alumina template was determined. (ii) The effect of thermal stresses (that appear in a nanowire after the cooling process) on the magnetic hysteresis loop for a square nanowires arrays was studied. The hysteresis loop of the nanowire system was computed using an Ising-type model in which the nanowire magnetization vector has two preferred directions along the nanowire's axis. For a given temperature, the switch between these states is determined by the energy barrier defined by the applied field, the magnetostatic interaction field, and by the magnetoelastic anisotropy field. The magnetocrystalline anisotropy field is considered along the nanowire's axis. (iii) Discussions about the influence of the thermal stresses on the reduced remanence and coercitivity field of the nanowire arrays. The shape of hysteresis loop is mainly influenced by the thermal stresses induced during the nanowire cooling process. The remanence magnetization depends on the size parameter of the nanowires and on the temperature.

II. MAGNETOELASTIC ENERGY

In this section, we have calculated the magnetoelastic anisotropy field of a Co nanowire from alumina template, starting from the thermal behavior during the cooling process to the temperature of 3 K. The determination of the magnetoelastic anisotropy field implies the knowledge of the internal stresses (radial, azimuthal, and axial stresses) which appear due to the forced cooling and to the constraints produced on the nanowire by the alumina membrane as a result of the difference between the thermal expansion coefficients of the two materials in contact. Let us consider a nanowire having length L and radius R_1, and the alumina membrane having the thickness R_2-R_1; R_2 is the total radius of the cylindrical system (cobalt nanowire+alumina membrane). We associate a cylindrical system of coordinates (r,θ,z) with the sample, having the Oz-axis along the nanowire's axis. During the cooling process, the thermal behavior of the system is described by the solution of the Fourier heat transport equation.[7] By imposing the initial temporal conditions for the temperature of the system $t=0$, $T_1(r=0,t=0)=T_r=300$ K, and $(\partial T_1/\partial r)|_{r=0}=0$, it results to the following expression:

$$T_1(r,t)=T_g+(T_r-T_g)I_0(r\sqrt{(2L/R_1)-n^2})e^{-n^2at}, \quad (r<R_1). \tag{1}$$

Figure 1 shows the radial distribution of the temperature in the system (nanowire+alumina membrane) at the moment $t_1=0.0001$ fs, for three values of the radius of the nanowire: 0.5, 0.7, and 1 nm, respectively.

Solving the displacement differential equation for our system,[9] the expressions of the thermal stresses in the nano-

[a)]Electronic mail: iordana@uaic.ro.

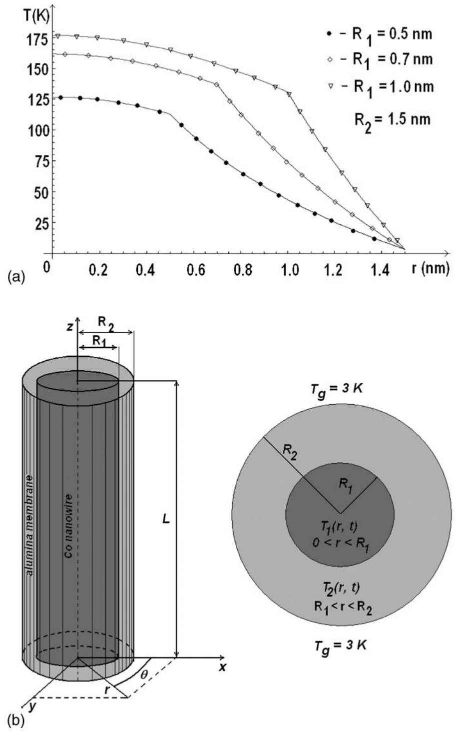

FIG. 1. The radial distribution of the temperature in the cross section of the system at the time $t=0.0001$ fs and three values of the nanowire's radius: 0.5, 0.7, and 1 nm. The radius of the system is $R_2=1.5$ nm.

wire can be obtained. In the following, we consider the axial stresses of the nanowire responsible for the uniaxial anisotropy of the nanowire. Figure 2, presents the dependence on the temperature of the axial stresses induced in the nanowire at the end of the cooling process. The axial stresses decrease with the increase of the temperature. The knowledge of the axial internal stresses after the cooling processes allow us to evaluate the magnetoelastic energy $E=3/2\lambda\sigma_{zz}$ and the magnetoelastic anisotropy field $h_s=3\lambda\sigma_{zz}/2K$ for a given nanowire system, where K is the anisotropy constant. The magnetoelastic anisotropy field increases with the increase of the temperature.

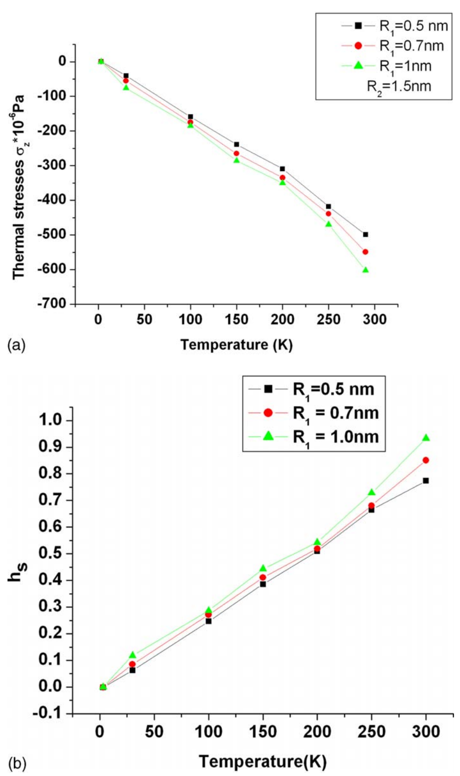

FIG. 2. (Color online) The dependence with the temperature of the axial stresses induced in the nanowire at the end of the cooling process (a) and magnetoelastic anisotropy field (b).

III. TEMPERATURE DEPENDENCE OF THE HYSTERESIS LOOP

In this section, we analyzed the temperature dependence of the hysteresis loop considering the magnetoelastic anisotropy field due to the thermal stresses and the magnetostatic interaction field, which appear in the vertically oriented, parallel magnetic nanowires ordered in a two dimensional square array. We assumed that nanowires are single domain and exhibit a magnetic anisotropy with an easy magnetization along the nanowire's axis. This fact will allow us to consider each one of such nanowire as a magnetic dipole. The dipole approximation was preferred because it reduces the computation time and gives a valuable estimation of the magnitude of the magnetostatic interaction between nanowires for typical nanowire arrays: with long wires and relatively large distance between wires.[10] A more complex evaluation of the interaction field will be presented in a future paper. The magnetostatic interaction field H_i created by the a dipole with moment m and length L at distance a (internanowire distance) in the perpendicular direction to the dipole is given by

$$H_i = \frac{1}{4\pi}\frac{m}{[a^2+(L/2)^2]^{3/2}}. \tag{2}$$

The sum of the fields created by the individual wires at a specified point represents the interaction field at that point. In our model, the total energy of the nanowires can be written as

$$E = KV\sin^2\theta - VM_sH\cos\theta + \frac{3\lambda\sigma}{2}\sin^2\theta, \tag{3}$$

where K is the anisotropy constant, V is the nanowire volume, M_s is the saturation magnetization of the nanowires, and θ is the angle between the magnetization vector and easy direction. The equilibrium positions of the polarization vector of the nanowire can be determined by minimizing the energy $dE/d\theta=0$.[11]

Using a Metropolis technique[12,13] for 20×20 nanowires considered as magnetic dipoles and considering the applied field being parallel with the axis of each nanowires, we obtained the hysteresis loops for the different values of temperatures in the range of 3–300 K. Figures 3(a) and 3(b) present the hysteresis loops for 3 and 200 K in the case of nanowire having radius $R_1=0.5$ nm, length $l=1000$ nm, and $a=3$ nm without and with stress term. The shape of hysteresis loops strongly depends on the magnetostatic interaction field H_i and thermal stresses. Considering the magnetic field applied parallel to the long axis of the nanowires, at the low

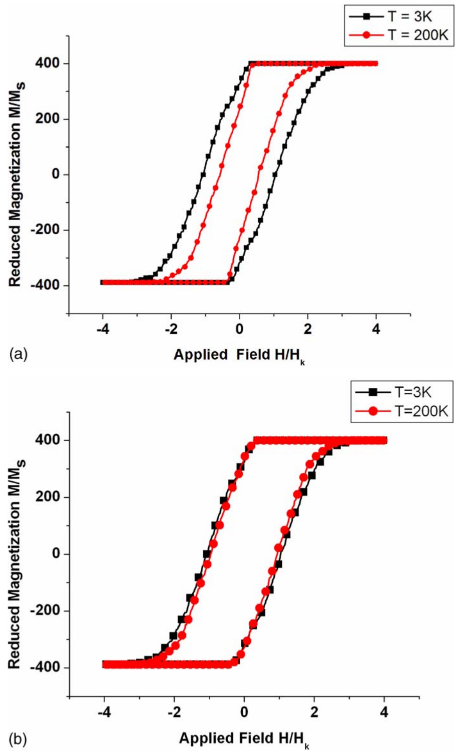

FIG. 3. (Color online) The temperature dependence of the histeresis loop: (a) without stresses and (b) with stresses.

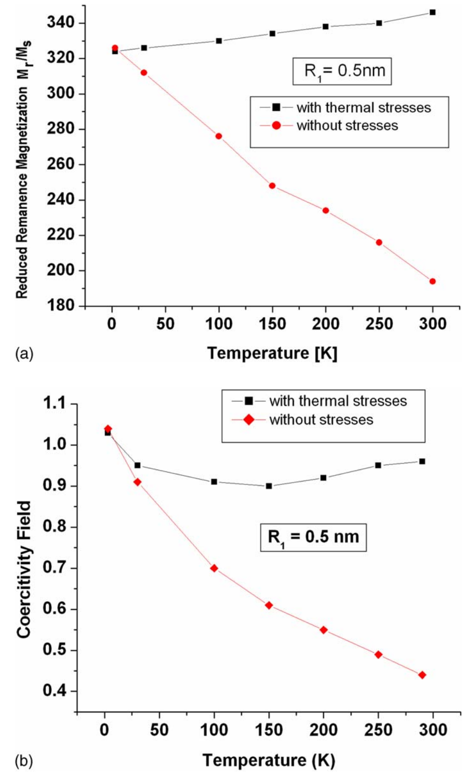

FIG. 4. (Color online) The temperature dependence of the remanent magnetization (a) and coercitive field (b) calculated considering thermal stresses and without thermal stresses.

temperatures, one can observe a square hysteresis curve. Figure 4 presents the temperature dependence of the reduced remanence (M_r/M_s) and coercitive field for two situations: the thermal stresses are not considered $(h_s=0)$ and the thermal stresses are considered $(h_s \neq 0)$.

In the case when the magnetoelastic energy is not considered, a decrease of the reduced remanent magnetization (M_r/M_s) was observed. When the magnetoelastic anisotropy due to the thermal stresses is considered, an increase of the reduced remanent magnetization was determined. This behavior was experimentally observed for a Co nanowire system embedded into an alumina template.[6] The coercitive field decreases with temperature in the case $h_s=0$, while in the presence of the thermal stresses, there is a easy increase with temperature.

IV. CONCLUSIONS

The thermal stresses from the nanowires and magnetostatic interactions have an essential role in defining the shape of the hysteresis loop of the nanowire arrays. The results show that the thermal stresses, which appear in a nanowire during the cooling process, influence the temperature dependence of the major hysteresis loop of the nanowire arrays. By calculating the magnetostatic interactions induced in Co nanowire arrays and thermal stresses, which appear after the cooling of the nanowires, information about magnetic behavior of these nanostructures can be obtained directly. The increase of the reduced remanent magnetization with the temperature was determined by numerical computation, considering the effect of the magnetoelastic energy in the nanowire system. This result could be an explanation for the experimental observed behavior in Ref. 6

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