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The effect of temperature on magnetostatic interactions in nanowires systems

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This paper analyzes the influence of the temperature on the magnetostatic behavior of nanowire arrays. The computation was done considering two nanowire arrays types: with honeycomb lattice and with square lattice. The hysteresis loop of the nanowires system was calculated using an Ising type model, in which the wires magnetization vector has two preferred directions along nanowires axis. The interaction field between wires was analyzed using the FORC (First Order Reversal curves) diagrams. It was observed that magnetostatic interaction field modify the shape of hysteresis loop. The hysteresis loop parameters and the superparamagnetic effects are directly related with the geometric parameters of the nanowire system.

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1. Introduction

Magnetic nanowires are scientifically interesting and have potential applications in many areas of advanced nanotechnology, including patterned magnetic media, nanosensors magnetic devices and materials for microwave applications [1, 3]. Using the electrodeposition technique and a porous anodic alumina it can be produced easily Fe, Co and Ni wires with diameters ranging from 4 to 200 nm, and lengths of up to few microns.

This paper presents a study of the magnetostatic interactions on the magnetic properties of Co nanowires arrays with different geometries: square lattice and hexagonal lattice. In order to calculate the hysteresis loop of the system of nanowires it was used an Ising-type model, in which each wire has a uniaxial anisotropy field. Magnetostatic interactions are calculated in the middle of each wire and a standard Metropolis-Monte-Carlo numerical procedure was used to evaluate which wire is reversing the magnetic moment. It was drawn the hysteresis loops for a set of geometrical parameters: diameter and length of wires and lattice constant for two temperatures $5K$ and $200K$. As it is expected, the interactions have an essential role in defining the shape of the hysteresis loop of the nanowire system.

The magnetostatic interactions between wires as function of the array lattice constant were analyzed using the FORC (First Order Reversal Curve) diagram. For a better comparison with the experiment results, two particular types of nanowires networks were considered: a. the distance between nanowire is the same for hexagonal and square lattice and b. the density of nanowire (number of wires per unit surface) is the same for hexagonal and square lattice. For analyzing of the effect of temperature on magnetostatic interactions two cases are considered: 1. the anisotropy constant and saturation magnetization depend on temperature and 2. no temperature variation of the anisotropy constant and saturation magnetization. For each considered case the dependence of the magnetic hysteresis loop parameters like the coercive force and squarness as function of the geometric wires parameters like wires diameters and lengths was drawn.

2. The numerical model for magnetization process

The considered systems consist of 2D network of magnetic nanowires. The Fig. 1 shows a view of these systems for two types of networks: with square and with hexagonal lattice.

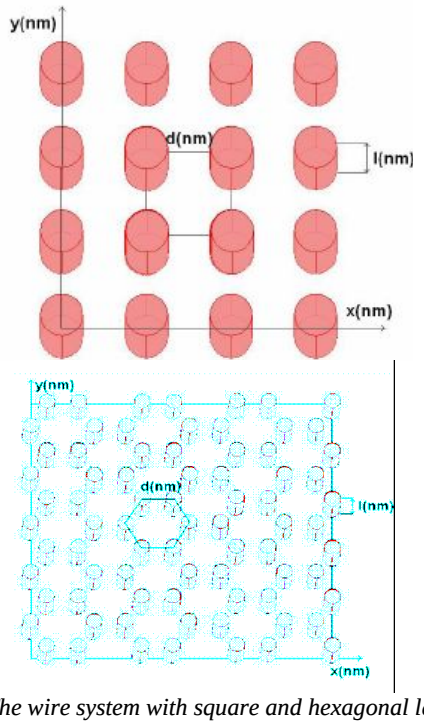

Fig.1.The wire system with square and hexagonal lattice.

The nanowires, considered as single domain, exhibit a magnetic anisotropy with an easy magnetization along the axis of the wire. The proposed model is based on the assumption of dipole approximation for a wire. This supposition is valid in condition when the length of the wire is larger then diameter (l>>D) [4]. For short wires this approximation is not applicable. Each wire from the system is in the field created by the wires ensemble. The magnetostatic interaction field $\vec{H}_i$ created by wires assumed as dipoles, with moment m and length l, in the given dipole place (i) is computing by summarizing the magnetostatic field of each wire [5]:

$$\vec{H}_i = \sum_j^{N^2} \frac{\vec{m}_{i,j}}{\left[a^2 + (l/2)^2\right]^{\frac{3}{2}}} \quad (1)$$

where a is the distance between nanowires considered in our calculation. The value interaction field depends on the wire magnetizations and consequently on the magnetization of the system. Inside a mono-domain nanowire the field lines are oriented from the north pole to the south pole and the fields are opposed to the magnetization of the material. Thus, the magnetic field inside the material tends to demagnetize the material with a field known as the demagnetizing field. Due to cylindrical symmetry, in our model it was used the Oz component of the demagnetizing field: $H_z = -N_z M_z$

where N_z demagnetization factor along the Oz axes, computed in the approximation of prolate shape sample [6]: $N_z = \frac{1}{c^2-1}\left(\frac{c}{\sqrt{c^2-1}}\ln(c+\sqrt{c^2-1}) - 1\right)$,

where $c = l/r$, l is the length of nanowire and r is the radius of nanowire.

For simulations, it was taken into account arrays of $60X60$ nanowires. Each nanowire (i, j) of 2D array has a normalized magnetic moment $\sigma_{i,j}$ which can takes the values ± 1 as function of moment orientation: up (+1) or down (-1). Considering the nanowire arrays as an assemble of uniaxial single domain particles having their easy axis aligned and the angle between this direction and applied field is zero, the heights of the energy barriers corresponding to the magnetic moment vector rotation in and out of the field direction of the selected wire [7]:

$$\Delta E_{\pm} = \frac{KV}{k_b T}\left[1 \pm H/H_k\right]^2 \quad (2)$$

where H_k is the uniaxial anisotropy field, K is the anisotropy constant of nanowire, V is the wire volume and H is the effective field acting on a wire.

For uniaxial crystal $K_1(T) = K_1(0)\left[M_s(T)/M_s(0)\right]^3$ [7]. The temperature dependence of the saturation magnetization $M_s(T)$ was considered as [8]

$$M_s(T)/M_s(0) \approx \sqrt{1 - T/T_c} \quad (3)$$

The effective field is given by the sum between the applied field H_{ap}, demagnetizing field H_d and interaction field H_i:

$$H = H_{ap} + H_d - H_i \quad (4)$$

It was considered that the interaction field is collinear with the applied field direction, but in opposite sense.

The uniaxial anisotropy field is defined as a Gaussian distribution:

$$P(H_k) = \exp\left[-(H_k - H_{k0})^2 / 2H_{k\sigma}^2\right] \quad (5)$$

where H_{k0} is the most probable anisotropy field of the ferromagnetic nanowire and $H_{k\sigma}$ is the standard deviation of the nanowire distribution (Fig. 2).

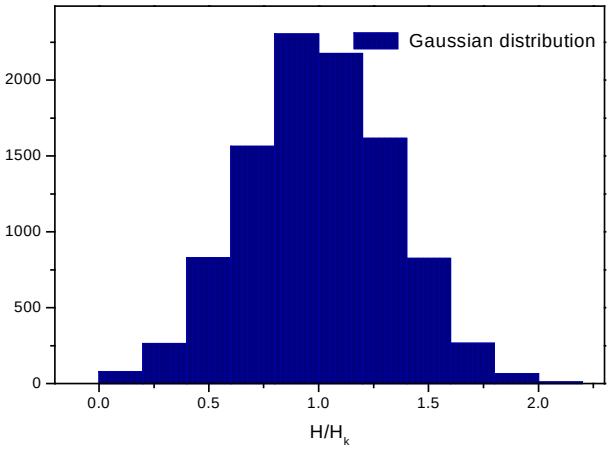

Fig. 2. Gaussian distribution of the anisotropy field

Using the Metropolis Monte Carlo method [9] we have drawn the hysteresis loops for different temperatures (T), diameters of nanowires (d) and distances between nanowires (a). In our simulation, the length is range of 50 - 200 nm and the diameter is range of 10 - 80 nm. The simulation started when every dipole are pointing up. The applied field is decreased with a given step to negative saturation and then is increased with the same step to positive saturation. Thus, it was obtained the hysteresis loop.

The magnetic dipole switches from up to down state with the probability given by

$$p = \exp\left[-\Delta E_{\pm}/(k_b T)\right] \quad (6)$$

where $\Delta E_{\pm}$ are the heights of the energy barriers corresponding to the stable equilibrium states

(magnetization vector parallel and antiparallel, respectively, with respect of the field direction), k_b is the Boltzmann constant and T is temperature. The numerical procedure is applied for all wires from the system. The net magnetization $\vec{M}$ of the system is the sum of the magnetization of constituent wires:

$$\vec{M} / M_s = (1/N^2)\sum_{i,j}\sigma_{i,j}\vec{z} \qquad (7)$$

($\vec{z}$ is a unit vector along the wire axes and M_s is saturation magnetization). The simulated hysteresis loop for the nanowire systems with square and hexagonal lattice at different temperatures are represented in the Fig. 3. The considered geometric parameters are: length of nanowire l = 200 nm, distance between nanowire a = 2 nm and nanowire diameter d = 1.2 nm. It is observed that the reduced remanence M_r is higher at hexagonal system than for square system.

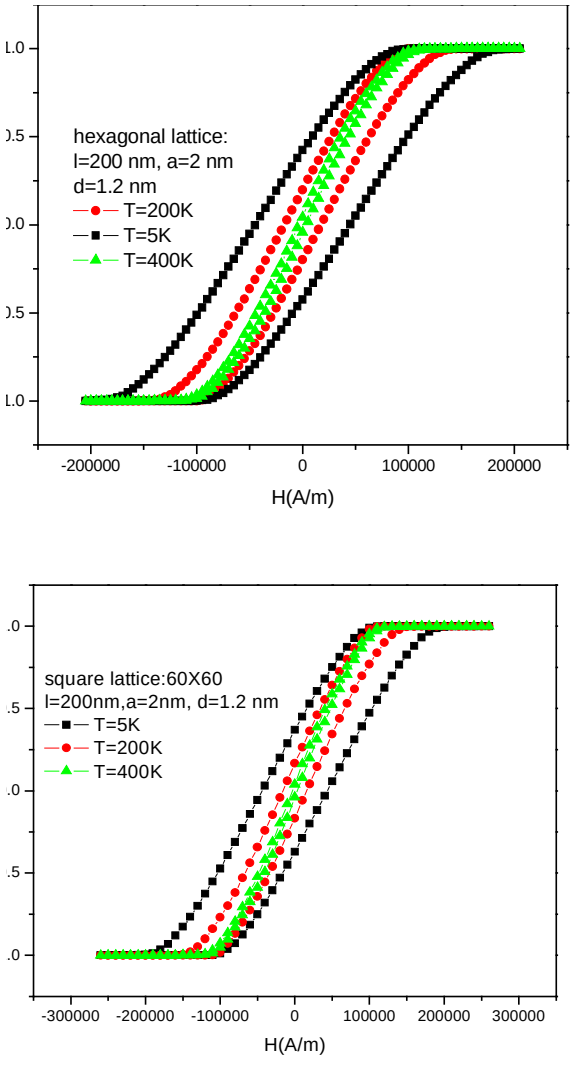

Fig. 3. The hysteresis loops for two types arrays: hexagonal system and square system for lattice constant a = 2 nm.

As it was expected, the increase of the temperature causes a decrease of the coercitive field (Fig. 4). When the coercitive field is zero, the nanowire system became superparamagnetic.

The superparamagnetism effect depends on the wires diameter. Therefore, for small nanowire diameters, this effect takes place at low temperature. At large diameter, the temperature is higher when superparamagnetism effect appears.

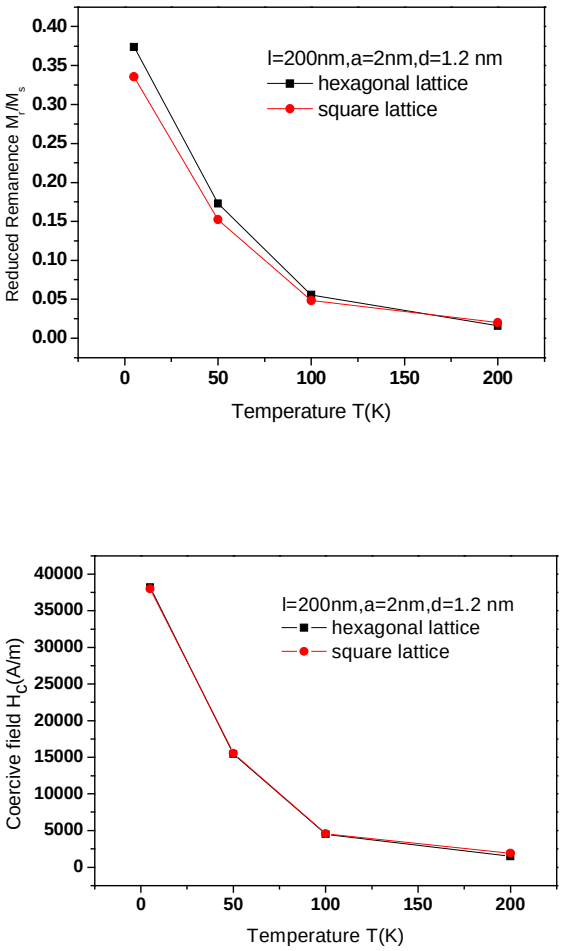

Fig.4. The squareness and coercive field function of temperature for given parameters in case 2.

In the same time the reduced magnetization and squarness M_r / M_s decreases at the increase of the temperature. If there is no difference between hexagonal and square systems for the coercive force, the squarness depends on type of lattice. Since the magnetostatic interaction is stronger at square system than hexagonal, the reduced remanence is bigger at hexagonal lattice than square lattice. At high temperature this behavior is not observed. For large distance between nanowire $a = 5$ nm the hysteresis loops are shown in the Fig.5. There are not significant differences between hysteresis curves of

hexagonal and square lattice systems. This could be explains by the low values the interaction field in this case compared with the case when the wires are more packed, for $a = 2$ nm.

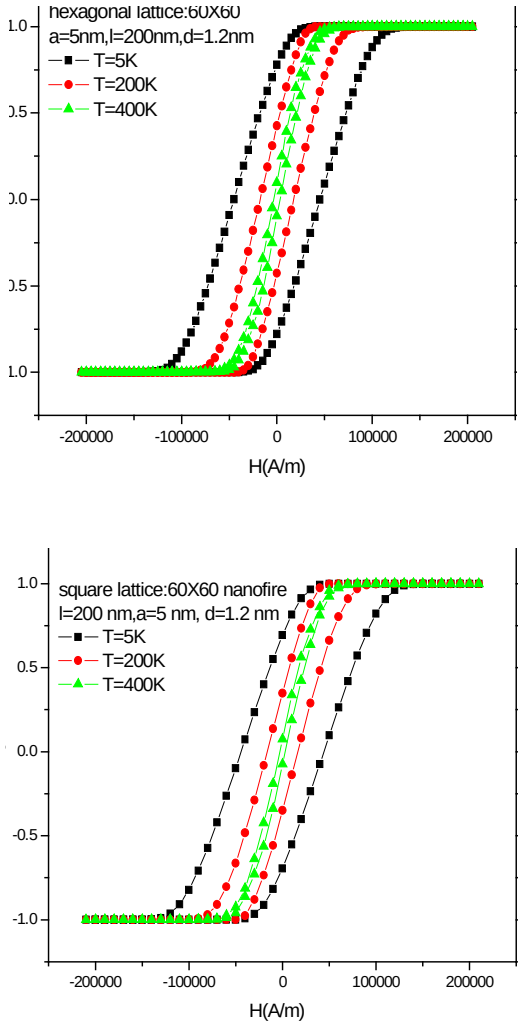

Fig.5. The hysteresis loops for two types arrays: a) hexagonal system and b) square system for lattice constant a = 5 nm.

In absence of magnetostatic interactions, the squarness of the hysteresis loop is equal to 1 and H_c increases with diameter of wires for both systems (square and hexagonal lattice).

In figures below, there are represented the coercive field dependence of nanowire with wires diameter for two cases: 1) $K = f(T)$, $M_s = f_1(T)$ (Fig.6) and 2) K, M_s are no dependent with temperature (Fig. 7).

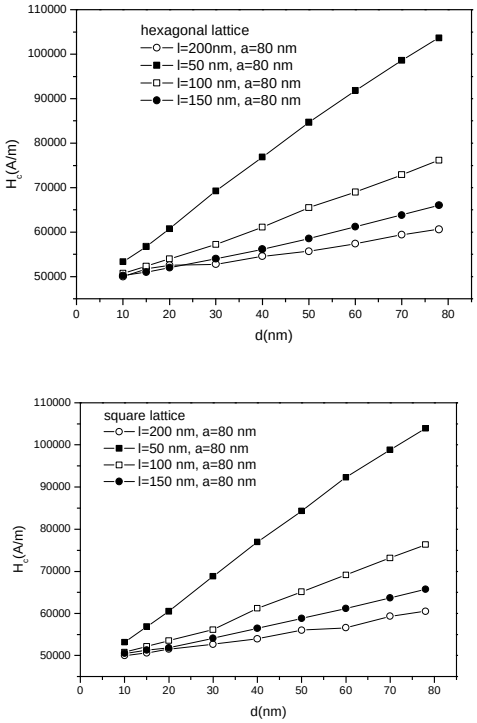

Fig.6. The coercive field as function of nanowires diameter for hexagonal and square lattice arrays with considered temperature dependence of the anisotropy constant and saturation magnetization (case 1).

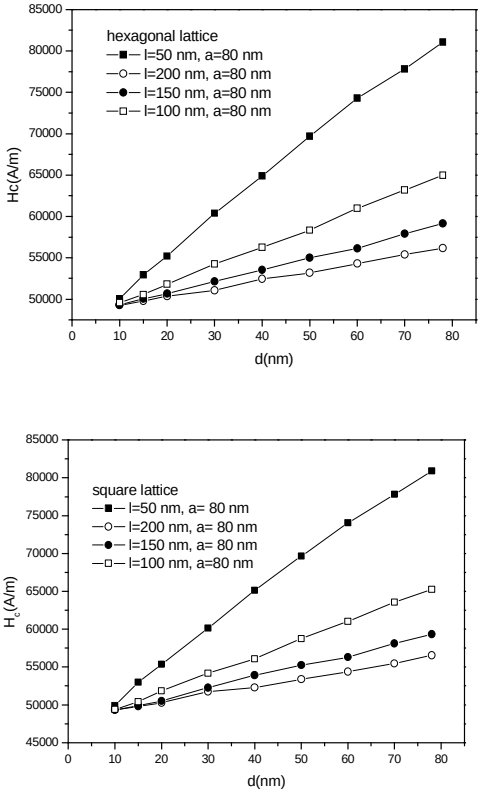

Fig.7. The coercive field as function of nanowires diameter for hexagonal and square lattice arrays with for given values of the anisotropy constant and saturation magnetization (case 2).

In the presence of magnetostatic interactions, the coercive force increase with nanowire diameter. The magnitude of coercive force is higher at length l = 50 nm and smaller at l = 200 nm. Therefore, coercive field increases with increasing of length of nanowire.

3. FORC diagrams

In order to analyze magnetostatic interaction, we used the FORC (First Order Reversal Curve) diagrams. These diagrams can be used for the characterization and investigation of any magnetic system.

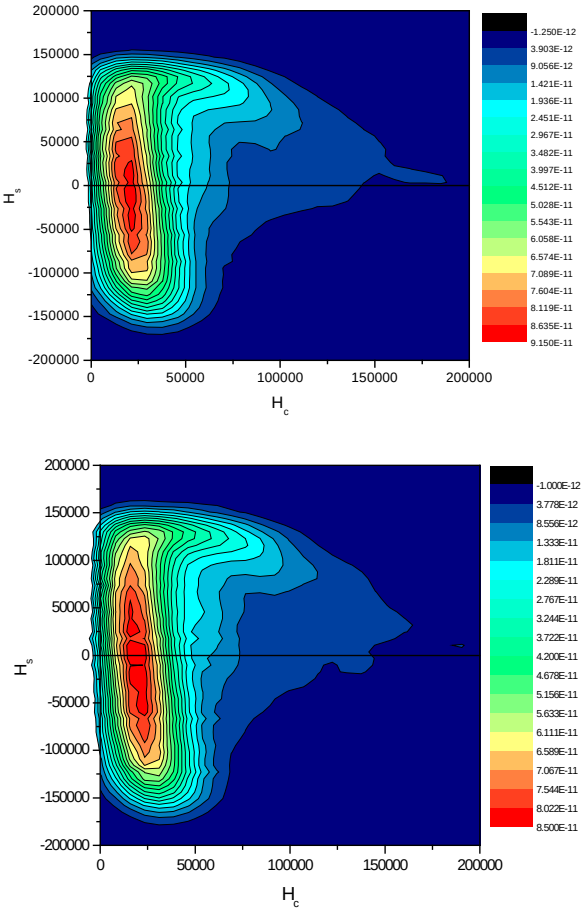

Fig.8. FORC diagrams for two nanowire systems at low temperature T=5K and a = 2nm, for hexagonal and square lattice.

The acquisition of a First Order Reversal Curve begins by saturating a system in a positive applied field. The applied field is decreased to a reversal field H_r, and a FORC is the magnetization curve that results when the field is increased back to saturation. The magnetization at applied field H on the FORC with the reversal field H_r is denoted by $M(H,H_r)$, where $H \geq H_r$ [10]. A FORC distribution is defined as the mixed second derivative:

$$\rho(H,H_r) \equiv -\frac{1}{2}\frac{\partial^2 M(H,H_r)}{\partial H \partial H_r} \tag{8}$$

For the plotting purpose of FORC distribution, it is better to change coordinates from $\{H_r, H\}$ to

$$H_c = \frac{H - H_r}{2}, H_s = \frac{H + H_r}{2} \tag{9}$$

A FORC diagram is a contour or 3D plot of $\rho(H_c,H_s)$. The H_c and H_s axis are referred to as to the coercivity and bias coordinate axis ($-H_i$), respectively. The FORC diagrams for two lattice constants are shown in Figs. 8-9.

From FORC diagrams results that the magnetostatic interaction is stronger for square system than hexagonal system, at low temperature. For high temperature, the thermal fluctuations are more powerful than energy barrier and the moments can be switched easily from one stable direction to another one.

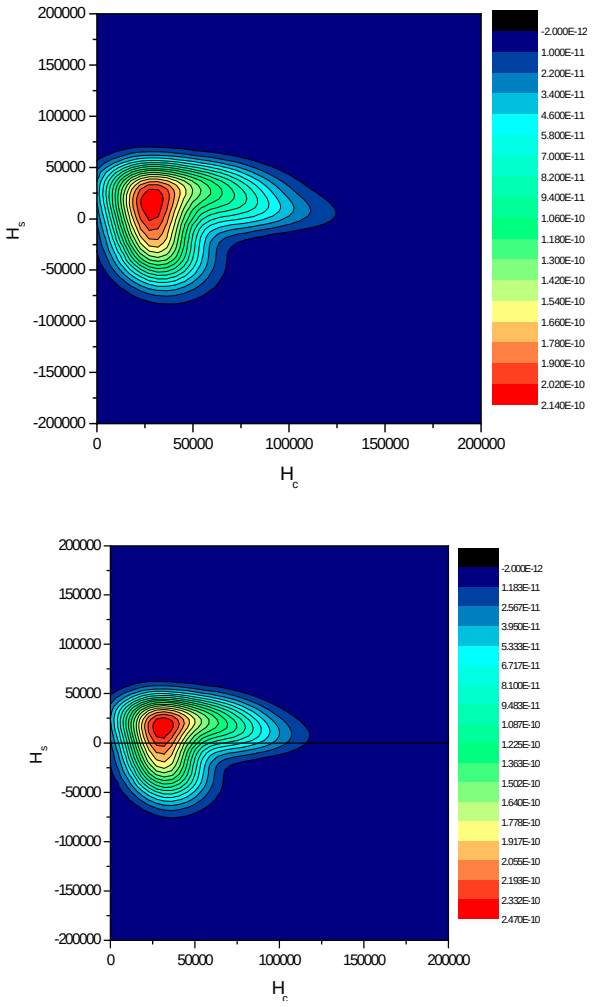

Fig.9. FORC diagrams for two nanowire systems at low temperature T=5K and the same distance (a = 5 nm) and the same nanowire density for hexagonal and square Lattice.

It was observed that for small distance between nanowire the interaction field is very strong and for large distances is weaker.

4. Conclusion

By calculation of the magnetostatic interactions induced in Co nanowire arrays we can obtain the information about magnetic behavior of these nanostructures. The results presented in this paper show the possibility to evaluate the magnetostatic interaction effect using FORC diagrams by changing the values of dimensional parameters of the arrays (length, radius of nanowires and inter-nanowire distance). The interaction field is stronger in square arrays than in hexagonal arrays. The squarness of the loop is bigger for arrays with low interaction field. The superparamgnetism effect depends on nanowire diameter.

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