International Letters of Chemistry, Physics and Astronomy
ISSN: 2299-3843, Vol. 53, pp 64-70
doi:10.18052/www.scipress.com/ILCPA.53.64
CC BY 4.0. Published by SciPress Ltd, Switzerland, 2015
Online: 2015-07-01

Effects of anisotropy and longitudinal field on a ferrimagnetic nanowire

Hadey K. Mohamad, Hassan Traikim Badh AL Hamade

Al-Muthanna University, College of Science, Department of Physics, Samawa, Iraq

E-mail address:hadeyk2002@yahoo.com

Keywords: Ferrimagnetic nanowire; Anisotropy; Longitudinal field; Compensation points.

ABSTRACT A ferrimagnetic nanowire consists of the spin-1/2 core and spin-1 outer shell has been studied. The general formula for the temperature dependence of the longitudinal magnetization of the system is given. The ferrimagnetic core-shell nanowire system exhibits two and three compensation points when the temperature of the system is changed at fixed values of the anisotropy of shell sublattice and longitudinal field, respectively. The competition among the exchange coupling between the outer shell and core, the outer shell coupling, the anisotropy, the applied field, and the temperature has a considerable effect on the characteristic of magnetic properties in a two-dimensional nanowire system.

1. INTRODUCTION

Magnetic nanowires, fabricated by various methods, represent an important family of magnetic nanostructures. So, these systems are of fundamental physical interest as magnetic force microscope(MFM) tips, in spintronics and biomedical applications[1,2]. Diverse applications require magnetic material having different magnetic properties. For example, perpendicular magnetic anisotropy is essential when nanowires are used as magnetic recording media[3]. The physical properties of one-dimensional nanostructures of magnetic materials are presently the subject of intensive research, taking into account the considerable attention they have recently received and the few cases reported. Much attention has directed towards the understanding of magnetization processes and related applications. Thus, magnetic nanowires have provided a highly successful test ground for understanding the microscopic mechanisms that determine macroscopically important parameters in the different applications[4,5]. The development of ferromagnetic nanowire arrays has revealed various unusual properties relevant to applications in high density data storage devices and in bioengineering applications[6]. Various efforts to fabricate one-dimensional, two-dimensional, and three-dimensional nanostructures have been made using conventional lithography, nanosphere lithography, di-block copolymers template, and anodic aluminum oxide (AAO) templates[6,7,8,9].

The aim of this research is to examine whether there is a compensation point in a ferrimagnetic core/shell nanowire with different single-ion anisotropies in the longitudinal field. Emphasis will be put on the effects of the anisotropy constants on the magnetic properties of the nanowire within the framework of mean-field theory. The work is outlined as follows: the formulation of model for a two-dimensional nanowire which consists of a ferromagnetic spin-1/2 core surrounded by an antiferromagnetic spin-1 shell with an antiferrimagnetic interface coupling. In the other section, the numerical results for the phase diagrams, the magnetization of the system are studied in detail. Finally, conclusion is presented.

2. THE MODEL

The model we consider is a ferrimagnetic nanowire consists of the spin-1/2 core for atoms C and spin-1 outer shell for atoms S, respectively. Then, the Hamiltonian of the system, in the absence of external magnetic field, can be written as[10]:

$$H = -J_1 \sum_{i,j} \mu_i^C S_j^S - J_2 \sum_{i,j} \mu_i^C \mu_j^C - J_3 \sum_{i,j} S_i^S S_j^S - D_S \sum_{j} (S_j^S)^2 \tag{1}$$

where $\mu = \pm 1/2$, for i, j belonging to core sublattice and $S = 0, \pm 1$, for i, j belonging to shell sublattice. J_1 is the nearest neighbour exchange parameter between magnetic atoms across the core and the outer shell. J_2 is the exchange interaction in the core. J_3 is the nearest neighbour exchange parameter between magnetic atoms at the outer shell. D_S is the anisotropy(i.e. crystal field) acting on the nearest-neighbor exchange parameter in the outer shell sublattice. The system is described, in the presence of an external magnetic field, by the following Hamiltonian:

$$H = -J_1 \sum_{i,j} \mu_i^C S_j^S - J_2 \sum_{i,j} \mu_i^C \mu_j^C - J_3 \sum_{i,j} S_i^S S_j^S - D_S \sum_j (S_j^S)^2 - h \sum_{i,j} (\mu_i^C + S_j^S) \tag{2}$$

The free energy of the system is obtained from a mean field calculation of the Hamiltonian[11],

$$A \le A_0 + \langle H - H_0 \rangle_0 \tag{3}$$

where A is the free energy of H given by relation (2), A_0 is the free energy of a paramagnetic phase and H_0 a trial Hamiltonian depending on variational parameters. In this research we consider one of the possible choices of H_0, namely:

$$H_0 = -\gamma_1 \sum_i \mu_i^C - \sum_j [\gamma_2 S_j^S + D_S (S_j^S)^2] - h \sum_{i,j} (\mu_i^C + S_j^S) \tag{4}$$

where γ_1 and γ_2 are the variational parameters related to the different spins μ_i^C and S_j^S respectively.

By minimizing the right hand of Eq.(3) with respect to variational parameters, we obtain the approximated

free energy, that:

$$\varphi = \frac{A}{N} = -\frac{1}{2\beta}[\ln(2\cosh\frac{1}{2}(\beta\gamma_1 + \Omega)) + \ln(2e^{\beta D_S}\cosh(\beta\gamma_2 + \Omega) + 1)]$$
$$+\frac{1}{2}[-zJ_1 m_C m_S - J_2 z m_C^2 - J_3 z m_S^2 + \gamma_1 m_C + \gamma_2 m_S] \tag{5}$$

where N is the total number of sites of lattice. Minimizing this expression with respect to γ_1, γ_2 we obtain,

$$\gamma_1 = J_1 z m_S + 2J_2 z m_C\ , \quad \gamma_2 = J_1 z m_C + 2J_3 z m_S \tag{6}$$

with,

$$m_C = \frac{1}{2}\tanh\frac{1}{2}(\beta\lambda_1 + \Omega) \tag{7}$$

$$m_S = \frac{2\sinh(\beta\lambda_2 + \Omega)}{2\cosh(\beta\lambda_2 + \Omega) + e^{-\beta D}} \tag{8}$$

where $\lambda_1 = J_1 z m_S + J_2 z m_C$, $\lambda_2 = J_1 z m_C + J_3 z m_S$, $\Omega = \beta h$, $\beta = \frac{1}{K_B T}$, z is the coordination number of the lattice.

It is worth noting that the ferrimagnetic case shows that the signs of sublattice magnetizations are different, and there may be a compensation point at which

the total longitudinal magnetization per site, that

$M = \frac{1}{5}(m_C + 4m_S)$ is equal to zero.

3. RESULTS AND DISCUSSION

In the present section, let us examine the sublattice magnetization dependence of the absolute temperature for a two-dimensional nanowire. For the set of values of the exchange interaction $J_1 = -1.2, J_2 = 1.5$, and $J_3 = 1.0$, Figs.(1,2,3) stands for the sublattices magnetizations versus the absolute temperature, in the absence of an external magnetic field, for different values of D_S / J_3. One can see that there is a response of the system for induction of one or two compensation points in the range of negative values of magnetic anisotropy, namely, $D_S / J_3 = -0.95, -1.0, -1.2$, respectively. Fig.(3) shows an interesting behaviour of thermal magnetization as a function of temperature, that we found $T_{k_1} = 0.209K^o$, $T_{k_2} = 0.568K^o$ for the compensation points, and $T_c = 13.083K^o$, for the transition temperature, respectively.

On the other hand, we also observe that the system has three compensation temperatures as an external magnetic field is applied. As shown from the two figures(4,5), the system may exhibit many compensation points in the thermal variation of the system magnetization, which can be obtained by solving the coupled equations(7,8), for m_C and m_S numerically, depending on the values of the applied magnetic fields, h / J_3, in the range of values of interest for longitudinal fields, when $h / J_3 = [-0.01, -0.02, 0.01, 0.02, 0.03]$, with values of anisotropy(i.e. crystal field) $D_S / J_3 = -0.95, -1.0, -1.2$, respectively, acting on the shell atoms on a two-dimensional nanowire. As can be seen, the compensation temperature appears due to entropy some spins can flip their directions. Thus, the shell sublattice magnetization m_S becomes more ordered than the core sublattice magnetization m_C for temperatures above the compensation temperature. So there is an intermediate point such that the cancellation is complete[10].

It is worth noting that there is no response of the system for induction of compensation points in the range of positive values of crystal fields, in contrast to negative ones influencing the existence and location of the compensation points.

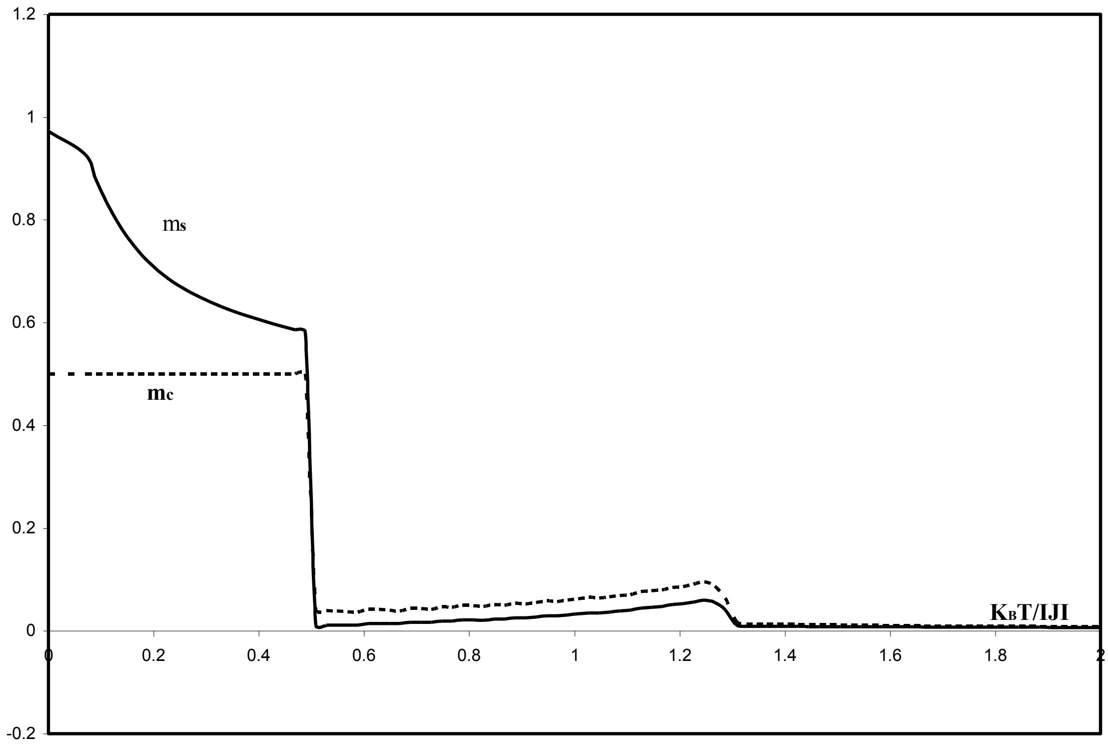

Fig.1. The temperature dependences of the sublattice magnetizations m_C , m_S for the mixed-spin ferrimagnetic nanowire, at a fixed value of $D_S / J_3 = -0.95$.

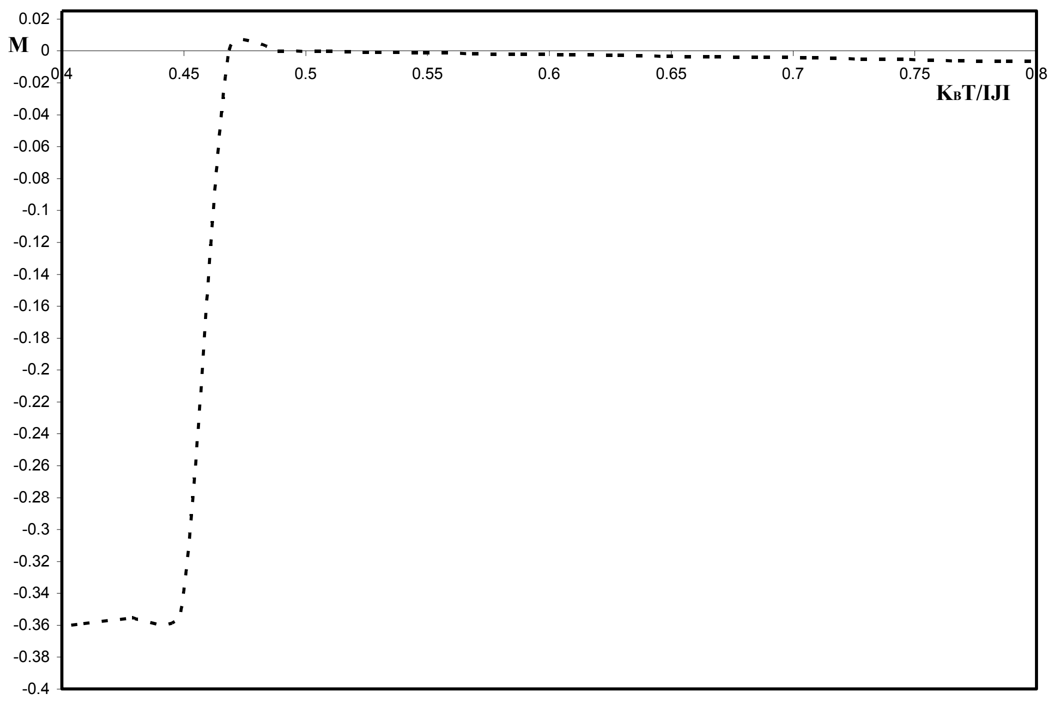

Fig.2. The temperature dependences of the sublattice magnetizations M , for the mixed-spin ferrimagnetic nanowire, at a fixed value of $D_S / J_3 = -1.0$.

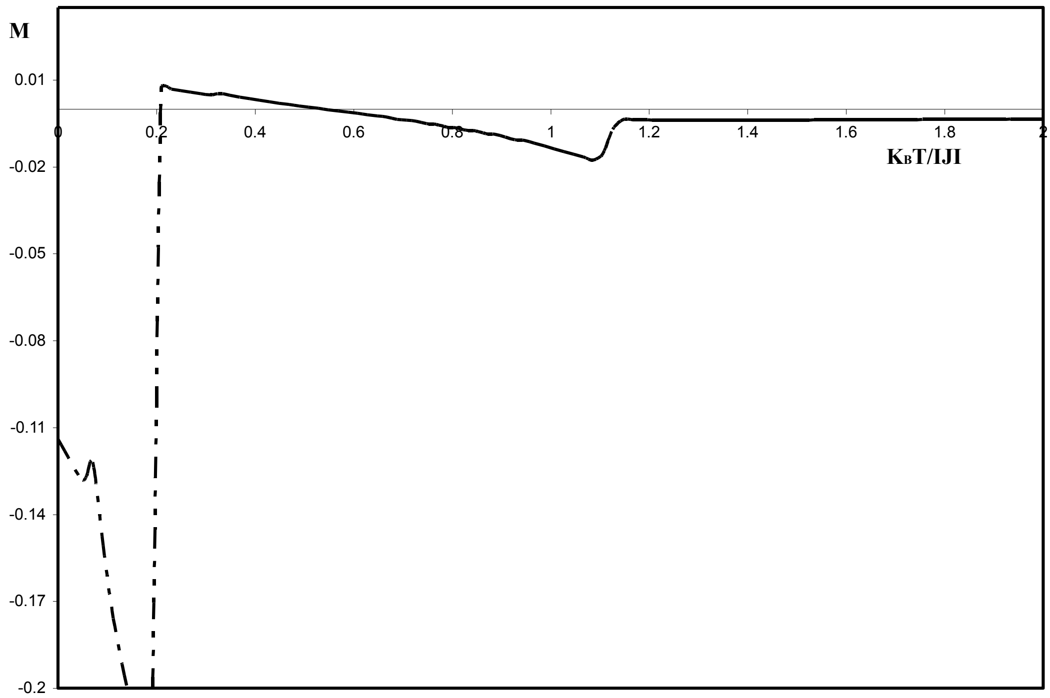

Fig.3. The temperature dependences of the sublattice magnetizations m_C, m_S for the mixed-spin ferrimagnetic nanowire, at a fixed value of $D_S / J_3 = -1.2$.

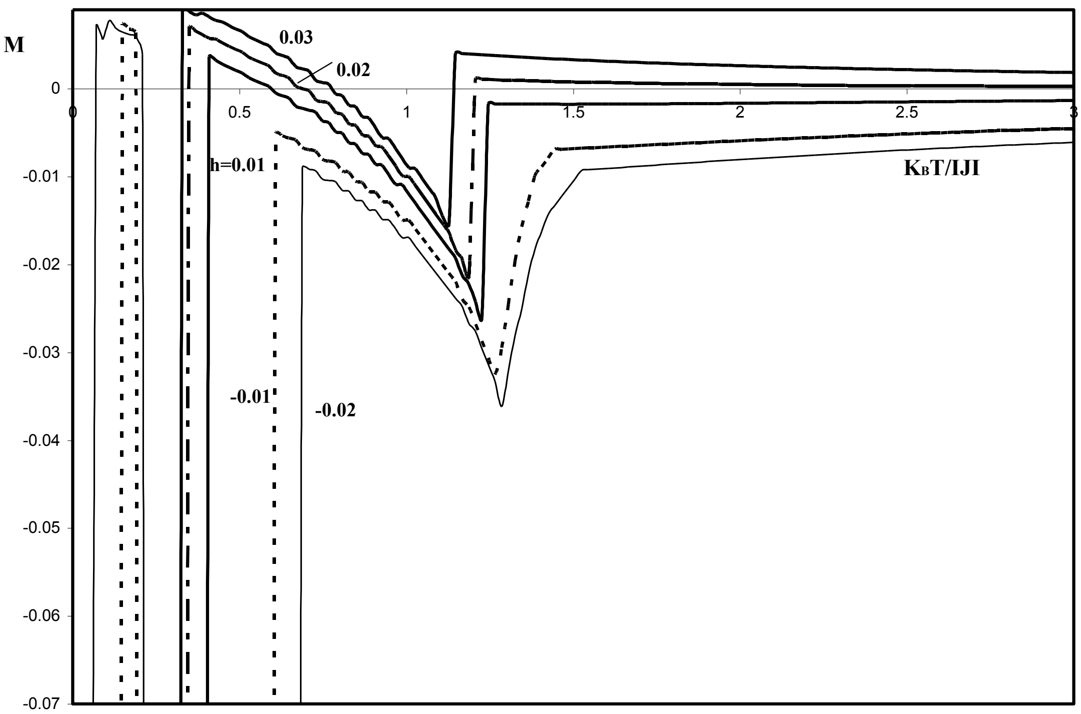

Fig.4. The temperature dependencies of the total magnetization M for the mixed-spin ferrimagnetic nanowire, for different values of h / J_3, at a fixed value of $D_S / J_3 = -0.95$.

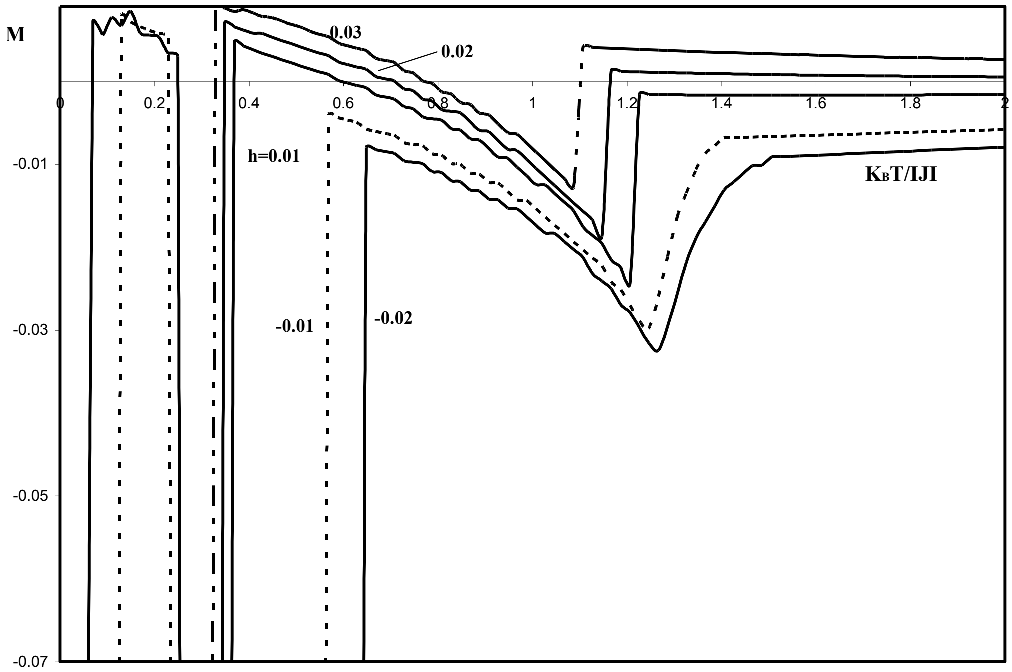

Fig.5. The temperature dependencies of the total magnetization M for the mixed-spin ferrimagnetic nanowire, for different values of h/J_3, at a fixed value of $D_S/J_3 = -1.0$.

4. CONCLUSIONS

We have developed the mean-field theory for a two-dimensional nanowire consisting of a ferromagnetic spin-1/2 core surrounded by an antiferromagnetic spin-1 shell with an antiferrimagnetic interface coupling. The magnetic properties of the system with different anisotropies have been found by solving the general expressions numerically. The magnetization curves show outstanding features(two compensation points). One can compare our results with those obtained in the mixed-spin(1/2,1) system and mixed-spin(1,3/2)one[10,13], in which the models exhibit a compensation temperature, respectively. It is noteworthy that there is no response of the system for induction of a compensation point in the range of positive values of crystal fields, in contrast to negative ones influencing the existence and location of the compensation points. It remains to mention that the present system may clearly exhibit three spin compensation temperatures for the magnetization curves labeled $h/J_3 = [0.01, 0.02, 0.03]$, when the values of the crystal field $D_S/J_3 = -0.95, -1.0$, at $T \neq 0$, for a square nanowire, that is, the magnetization behaves as an N-type curve in Nee'l's classification[10,13]. Finally, we can conclude by saying that the two-mixed ferrimagnetic nanowire system with different crystal and longitudinal fields may be a fruitful system from both theoretical and experimental points of view.

References

[1] G. Beck, K. Petrikowski , H. R. Khan, "Microstructure Analysis in Materials Science", Freiberg, 2005.

[2] M. U. Lutz, U. Weissker, F. Wolny, C. Muller, M. Loffler, T. Muhl, A. Leonhardt, B. Buchner, R. Klingeler, "Magnetic properties of α-Fe and Fe3C nanowires", J. Physics: Conference Series, **200** , 2010,072062.

[3] Liying Zhang , Yafei Zhang, " Fabrication and magnetic properties of Fe3O4 nanowire arrays in different diameters", J. Magn. Magn. Mater., 321, 2009,L15.

[4] V. F. Puntes, K. M. Krishnan, A. P. Alivisatos, " Colloidal nanocrystal shape and size control: The case of cobalt ", Science, 291, ,2001,2115.

[5] D.J.Sellmyer, M. Zheng, R. Skomski," Magnetism of Fe, Co and Ni nanowires in self-assembled arrays", J. Phys.: Condens. Matter ,13, 2001,R433.

[6] A.K. Srivastava, R.S. Singh, K.E. Sampson, V.P. Singh, R.V. Ramanujan, "Templated assembly of magnetic cobalt nanowire arrays", Metallurgical and Materials Transactions A ,38A, 2007,717.

[7] A.K. Srivastava, S. Madhavi, T.J. White, R.V. Ramanujan," Template assisted assembly of cobalt nanobowls arrays", J. Mater. Chem.,15, 2005,4424.

[8] A.K. Srivastava, S. Madhavi, T.J. White, R.V. Ramanujan," The processing and characterization of magnetic nanobowls", Thin Solid Films, 505, 2006,93.

[9] C.A. Ross, " Patterned magnetic recording media", Annu. Rev. Mater. Res., 31, 2001,203.

[10] E. Vatansever, H. Polat, " Monte Carlo investigation of a spherical ferrimagnetic core–shell nanoparticle under a time dependent magnetic field" , J.Magn.Magn. Mater.,343,2013,221.

[11] Fathi Abubrig, " Mean-Field Solution of the Mixed Spin-2 and Spin-5/2 Ising Ferrimagnetic System with Different Single-Ion Anisotropies", Open J. Applied Sciences, 3,2013, 270.

[12] M. Godoy, V.S. Leite, W. Figueiredo, "Mixed-spin Ising model and compensation temperature", Phys. Rev. B, 69,2004, 054428.

[13] Ersin Kantar, Yusuf Kocakaplan, "Hexagonal type Ising nanowire with core/shell structure: The phase diagrams and compensation behaviors", Solid Stat.Commun.,177, 2014,1-6.