Physica A 434 (2015) 194–200

Contents lists available at ScienceDirect

Physica A

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

Effective distance of a ferromagnetic trilayer Ising nanostructure with an ABA stacking sequence

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HIGHLIGHTS

- We studied the magnetic properties of a trilayer Ising nanostructure (TLINS).
- Magnetic properties of TLINS depend greatly on the distance between layers.
- We suggest that there is an effective distance (d_{eff}) between the layers.
- Interaction between layers is strong at $d \leq d_{eff}$ but almost zero at $d \geq d_{eff}$.
- H_C and T_C are independent of the distance and almost constant at $d \geq d_{eff}$.

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 16 March 2015
Available online 12 April 2015

Keywords:
ABA stacking
Distance effect
Effective field theory
Trilayer Ising nanostructure

ABSTRACT

In this study, we investigated the effects of the distance between two nearest-neighbor layers on the magnetization and hysteresis properties (remanence, coercivity and loop area) of a ferromagnetic trilayer Ising nanostructure (TLINS) with an ABA stacking sequence using the Kaneyoshi approach within the effective field theory. We found that the ferromagnetic properties of the TLINS were highly dependent on the distance (d) between the layers. The layers had strong interactions at a certain minimum distance (d_{min}) but no interactions at a certain maximum distance (d_{max}). Thus, we suggest that there is an effective distance (d_{eff}) at $d_{min} \leq d_{eff} \leq d_{max}$ for the TLINS. We observed that the critical temperature increased sharply as the distance decreased at $d \leq d_{min}$, T_C increased slowly as the distance decreased at d_{eff}, and T_C had a certain constant value at $d \geq d_{max}$. The critical field points increased rapidly as the distance decreased and H_C had different values for the central and edge atoms at $d \leq d_{min}$. H_C increased slowly as the distance decreased at d_{eff} and H_C had the same value for the central and edge atoms at d_{eff}, while H_C had a certain constant value at $d \geq d_{max}$. Distance had no effect on the critical temperature and critical field points of the TLINS and they had a constant value at $d \geq d_{max}$; thus, the TLINS behaved as a single layer Ising nanostructure at great distances.

1. Introduction

The ferromagnetism of graphene-based materials has attracted much interest due to its possible applications in spintronics devices. Examples include the ferromagnetism of nitrogen-doped graphene oxide [1], hydrogen-functionalized epi-

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http://dx.doi.org/10.1016/j.physa.2015.04.002
0378-4371/

taxial graphene on SiO [2], graphite oxide and reduced graphene oxide [3,4], nanomesh graphene [5], activated graphene oxide [6], graphene samples prepared by the thermal exfoliation of graphitic oxide, the conversion of nanodiamond, arc evaporation of graphene in hydrogen [7], reduced graphene nanoplatelets [8], few-layer graphene samples [9] and nickel-adsorbed graphene [10]. The magnetic properties of nanostructures have been investigated widely using the Kaneyoshi approach [11–28] within the effective field theory, such as the magnetic properties of Ising nanowires [29–40], core/shell Ising nanostructures [41–43], Ising nanotubes [44,45], ferroelectric thin film [46], and two layer Ising nanographene at different temperatures [47].

However, the effects of distance on the magnetic properties of multilayer Ising nanostructures have not been investigated in previous studies. Therefore, in the present study, we investigated the effects of distance on the magnetic properties of a ferromagnetic trilayer Ising nanostructure (TLINS) with an ABA stacking sequence. In particular, we focused on the theoretical and experimental analysis of multilayer graphene systems reported in previous studies. The theoretical results that we obtained for the TLINS agreed with the theoretical and experimental results reported for previous systems. We compared our theoretical results based on the effect of the number of layers (thickness) with those described in our previous study [47] and those in Refs. [48–52]. In our previous study, we investigated the magnetic properties of two layer Ising nanographene for $d = 1$, where we found that the critical phase transition of the two layer Ising nanographene occurred at $T_C = 2.12\, J/k_B$, whereas it occurred at $T_C = 2.37\, J/k_B$ for the TLINS with $d = 1$ in the present study. Similarly, the critical field points of two layer Ising nanographene were obtained at $H_C = \pm 0.44$, whereas they occurred at $H_C = \pm 0.58$ for the TLINS at $T = 1$ and $d = 1$ in the present study. Clearly, the critical temperature and critical field points of multilayer nanostructures increase with the number of layers. These results demonstrate that T_C and H_C are highly dependent on the number of layers in multilayer nanostructures. Therefore, these results agree with those reported in Refs. [48–52], which showed that the properties of multilayer graphene structures are highly dependent on the number of layers (thickness), the stacking sequence, and uniformity.

Moreover, our theoretical analysis of distance effects agrees with the theoretical results reported by Liu based on the Lennard-Jones potential, which showed that the friction behavior depends significantly on the interlayer separation distance (h) [53]. Our findings also agree with the theoretical results obtained by Zhong and Zhang using a multiple-scattering method, which showed that the energy spectra for multilayer photonic structures analogous to multilayer graphene structures with AAA, ABA, and ABC stacking are highly dependent on the distances between the layers, the stacking number in the layers, and the type of stacking [54]. Similarly, we found that the magnetic properties (magnetization and hysteresis) of the ferromagnetic spin-1/2 TLINS were highly dependent on the distances (d) between the layers. Furthermore, based on this distance dependency, we suggest that there is an effective distance (d_{eff}) for the TLINS, and we found that the magnetic properties of the TLINS did not change as the distance increased for $d \geq d_{\text{eff}}$, whereas they changed rapidly as the distance decreased for $d \leq d_{\text{eff}}$.

The remainder of this paper is organized as follows. In Section 2, we describe the theoretical method. In Section 3, we present our theoretical results and discussion. We give our conclusions in Section 4.

2. Theoretical method

We investigated the effect of distance on the magnetic properties of the ferromagnetic ($J_{\text{int}} > 0$) spin-1/2 TLINS shown in Fig. 1 based on the effective field theory. Each site in Fig. 1 is occupied by the spin-1/2 Ising particle.

Using the Kaneyoshi approach [11–28], the Hamiltonian of the TLINS is given by,

$$\mathcal{H} = -J_{\text{Central}} \sum_{\langle c1c2\rangle} S^z_{c1} S^z_{c2} - J_{\text{Int}} \sum_{\langle c2e1\rangle} S^z_{c2} S^z_{e1} - J_{\text{Edge}} \sum_{\langle e1e2\rangle} S^z_{e1} S^z_{e2} - J_{\text{Layer}} \sum_{\langle l1l2\rangle} S^z_{l1} S^z_{l2} - H \left(\sum_c S^z_c + \sum_e S^z_e \right) \tag{1}$$

where J_{Central} is the exchange interaction between two nearest-neighbor central atoms (m_{c1} and m_{c2}) in the TLINS. J_{Int} is the exchange interaction between two nearest-neighbor magnetic atoms, one of which is the central atom and the other is an edge atom of the TLINS. J_{Edge} is the exchange interaction between two nearest-neighbor edge atoms (m_{e1} and m_{e2}) in the TLINS. J_{Layer} is the exchange interaction between two nearest-neighbor magnetic atoms, one of which is in the bottom layer and the other is in the upper layer. $S^z = \pm 1$ is the Pauli spin operator. H is the external magnetic field.

The TLINS shown in Fig. 1 has four different magnetizations: m_{c1} and m_{c2} are the magnetization of the central atoms, and m_{e1} and m_{e2} are the magnetization of the edge atoms according to their nearest-neighbor atoms. Thus, m_{c1} has three nearest-neighbor central atoms (m_{c2}), m_{c2} has one nearest-neighbor central atom (m_{c1}) and two nearest-neighbor edge atoms (m_{e1}), m_{e1} has one nearest-neighbor central atom (m_{c2}) and one nearest-neighbor edge atom (m_{e2}), and m_{e2} has two nearest-neighbor edge atoms (m_{e1}). In addition, each magnetic atom in the layers has one nearest-neighbor atom, which is in the nearest-neighbor layer [47].

Using the Kaneyoshi approach [11–28], the magnetizations are given by

$$m_{c1} = [\cosh(J_1\nabla) + m_{c1}\sinh(J_1\nabla)]\,[\cosh(J_c\nabla) + m_{c2}\sinh(J_c\nabla)]^3\, F_{s-1/2}(x)\big|_{x=0},$$

$$m_{c2} = \left[\cosh\left(\frac{J_1}{2}\nabla\right) + m_{c2}\sinh\left(\frac{J_1}{2}\nabla\right)\right][\cosh(J_c\nabla) + m_{c1}\sinh(J_c\nabla)] \times [\cosh(J_{\text{Int}}\nabla) + m_{e1}\sinh(J_{\text{Int}}\nabla)]^2\, F_{s-1/2}(x)\big|_{x=0},$$