Physica E 61 (2014) 101–106

Contents lists available at ScienceDirect

Physica E

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

Surface effects on magnetic and thermodynamic properties in nanoscale multilayer ferrimagnetic films

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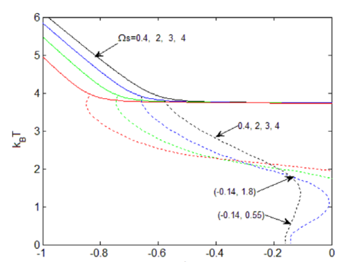
HIGHLIGHTS

- A ferrimagnetic nanoscale multilayer film has a simple cubic lattice.
- The formula of the magnetization and the internal energy is given.
- Surface effects on magnetic and thermodynamic properties have been studied.

GRAPHICAL ABSTRACT

Phase transition curves of nanoscale multilayer ferrimagnetic films may show compensation behavior, which mainly comes from different characteristic thermal variations of the sublattice magnetizations.



ARTICLE INFO

Article history:
Received 2 February 2014
Accepted 24 March 2014
Available online 1 April 2014

Keywords:
Nanoscale multilayer ferrimagnetic film
Two compensation temperature
Magnetization
Surface parameter

ABSTRACT

Magnetic and thermodynamic properties of a nanoscale multilayer ferrimagnetic films have been studied within the effective-field theory with correlations. The general formula for magnetization and internal energy is given. Some interesting results have been shown in the phase diagrams, for example two compensation points exist in the range of surface physical parameters. The competition among the surface exchange coupling, the surface single-ion anisotropy and the surface transverse field have great influences on the magnetization, the internal energy and the specific heat in the nanoscale multilayer ferrimagnetic films.

1. Introduction

Regarded multilayer magnetic thin films as a new material, it has been paid considerable attention because of its distinguishing shape and behavior. Especially ferrimagnetic thin films can be applied into technological uses, such as ultrahigh density recording medium [1–5]. A few experimental investigations have shown that bimetallic molecular-based magnets $CsMn^{II}$ $[Cr^{III}$ $(CN)_6]$ or $Fe^{II}Fe^{III}(C_2O_4)_3$ have layered and ferrimagnetism. The ferrimagnetic exchange coupling exists between Mn^{II} (Fe^{II}) and Cr^{III} (Fe^{III}) on the intralayer, and the ferromagnetic exchange coupling is seen between the interlayer. Meanwhile, compensation behavior is also observed in them. As well-known, compensation behavior is important for magnetic memory, which is strongly influenced by finite size and surface effects. One of the advantages of molecular-based magnets are they can be obtained by selection of suitable spin sources and coordinating ligands [6,7]. In addition rare-earth/transition metal of multilayer (such as Tb/Fe multilayer) has displayed ferrimagnetic characteristics. Its phase diagrams and magnetizations strongly depend on the thickness of rare-earth/transition metal layer. This means that the surface parameters and the thickness of layer may control the magnetic properties of the multilayer [8–10]. On the other hand, the magnetic thin film has been described by the Ising model. Without introducing

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http://dx.doi.org/10.1016/j.physe.2014.03.020
1386-9477/

mathematical complexities, Kaneyoshi has successfully applied the effective-field theory to magnetic Ising thin films [11–15] and nanoscale thin films [16–18]. Bouhou et al. have studied the thin films by Monte Carlo simulation [19]. However they have not considered the influences of both the surface single-ion anisotropy and the surface transverse fields on the magnetic films in those references mentioned above. Also the single-ion anisotropy plays an important role in the magnetic film and the nano-structure [20–22]. In our previous work, we have studied magnetic properties of the bilayer thin films and nano-structure by the effective-field theory with correlations [23–27]. The purpose of this work is to study the magnetic properties of the nanoscale multilayer thin films. The influence of the surface parameters on the phase diagram, the magnetization and the thermodynamic properties is investigated by the effective-field theory. Whether this can show some interesting results, such as two compensation points existing? Two compensation points may be of great technological importance, since only a small driving field can change the sign of the remanent magnetization between these points. In fact, this property may open a new and useful possibility for the high-density magnetic storage media.

The paper is organized as follows. In Section 2, we define the model and describe the Hamiltonian of this model. In Section 3, the numerical results of the phase diagrams, the magnetization, the internal energy and the specific heat are discussed in detail. Finally, some conclusions are given in Section 4.

2. Formulations

A ferrimagnetic nanoscale multilayer film is supposed to have a simple cubic lattice consisting of N parallel square lattice layers, and each layer is parallel to the (001) surfaces. The 3D layered square lattice is shown in Fig. 1. As mentioned in the Introduction,

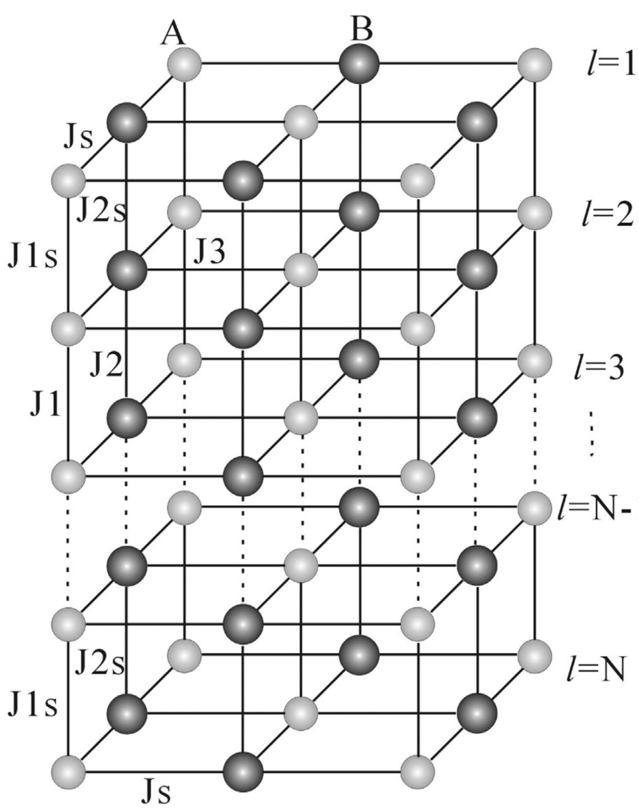

Fig. 1. 3D layered square lattice. The gray circles represent sublattice A with spin-3/2. The black circles represent sublattice B with spin-5/2.

two ions are from Cr^{III} and Mn^{II} whose values of spin are 3/2 and 5/2, respectively. The Hamiltonian of the system is given by

$$H=-J_{1l}\sum_{i,i'}S_i^zS_{i'}^z-J_{2l}\sum_{j,j'}\sigma_j^z\sigma_{j'}^z-J_{3l}\sum_{i,j}S_i^z\sigma_j^z-D_a\sum_i(S_i^z)^2-D_b\sum_j(\sigma_j^z)^2-\Omega_l\left(\sum_i S_i^x+\sum_j\sigma_j^x\right) \quad (1)$$

where S_i^z and σ_j^z are spin-3/2 and spin-5/2 on sublattices A and B, respectively. The first three sums run over all nearest-neighbor pairs in the interlayer. $J_{1l}(>0)$ and $J_{2l}(>0)$ are the interlayer exchange coupling and $J_{3l}(<0)$ is the intralayer exchange coupling. D_a and D_b are the single-ion anisotropies coming from sublattices A and B, respectively. Ω_l is the transverse field. The exchange couplings, the single-ion anisotropies and the transverse fields are not uniform in the different layers. In the surface layer $J_{1l}=J1s$, $J_{2l}=J2s$, $J_{3l}=Js$, $D_a=Das$, $D_b=Dbs$, and $\Omega_l=\Omega_s$, in the other layers $J_{1l}=J1$, $J_{2l}=J2$, $J_{3l}=J3$, $D_a=D1$, $D_b=D2$, and $\Omega_l=\Omega$.

The surface magnetizations $M_{A1(N)}$ and $M_{B1(N)}$ in the z-direction based on the effective-field theory are of the form [11–18,23–27]:

$$M_{A(B)1}=M_{A(B)N}=\left[\cosh(J_S\eta_{B(A)1}\nabla)+\frac{M_{B(A)1}}{\eta_{B(A)1}}\sinh(J_S\eta_{B(A)1}\nabla)\right]^4\times\left[\cosh(J_{1(2)S}\eta_{A(B)2}\nabla)+\frac{M_{A(B)2}}{\eta_{A(B)2}}\sinh(J_{1(2)S}\eta_{A(B)2}\nabla)\right]\times F_{A(B)}(x)|_{x=0} \quad (2)$$

Each layer magnetizations $M_{A(B)P}$ are given by

For $P=2$ or $P=N-1$

$$M_{A(B)P}=\left[\cosh(J_3\eta_{B(A)P}\nabla)+\frac{M_{B(A)P}}{\eta_{B(A)P}}\sinh(J_3\eta_{B(A)P}\nabla)\right]^4\times\left[\cosh(J_{1(2)S}\eta_{A(B)P-1}\nabla)+\frac{M_{A(B)P-1}}{\eta_{A(B)P-1}}\sinh(J_{1(2)S}\eta_{A(B)P-1}\nabla)\right]\times\left[\cosh(J_{1(2)}\eta_{A(B)P+1}\nabla)+\frac{M_{A(B)P+1}}{\eta_{A(B)P+1}}\sinh(J_{1(2)}\eta_{A(B)P+1}\nabla)\right]\times F_{A(B)}(x)|_{x=0} \quad (3)$$

For $3\le P\le N-2$

$$M_{A(B)P}=\left[\cosh(J_3\eta_{B(A)P}\nabla)+\frac{M_{B(A)P}}{\eta_{B(A)P}}\sinh(J_3\eta_{B(A)P}\nabla)\right]^4\times\left[\cosh(J_{1(2)}\eta_{A(B)P-1}\nabla)+\frac{M_{A(B)P-1}}{\eta_{A(B)P-1}}\sinh(J_{1(2)}\eta_{A(B)P-1}\nabla)\right]\times\left[\cosh(J_{1(2)}\eta_{A(B)P+1}\nabla)+\frac{M_{A(B)P+1}}{\eta_{A(B)P+1}}\sinh(J_{1(2)}\eta_{A(B)P+1}\nabla)\right]\times F_{A(B)}(x)|_{x=0} \quad (4)$$

and

For $P=1$ or $P=N$

$$\eta^2_{A(B)1}=\eta^2_{A(B)L}=\left[\cosh(J_S\eta_{B(A)1}\nabla)+\frac{M_{B(A)1}}{\eta_{B(A)1}}\sinh(J_S\eta_{B(A)1}\nabla)\right]^4\times\left[\cosh(J_{1(2)S}\eta_{A(B)2}\nabla)+\frac{M_{A(B)2}}{\eta_{A(B)2}}\sinh(J_{1(2)S}\eta_{A(B)2}\nabla)\right]\times G_{A(B)}(x)|_{x=0} \quad (5)$$

For $P=2$ or $P=N-1$

$$\eta^2_{A(B)P}=\left[\cosh(J_3\eta_{B(A)P}\nabla)+\frac{M_{B(A)P}}{\eta_{B(A)P}}\sinh(J_3\eta_{B(A)P}\nabla)\right]^4\times\left[\cosh(J_{1(2)S}\eta_{A(B)P-1}\nabla)+\frac{M_{A(B)P-1}}{\eta_{A(B)P-1}}\sinh(J_{1(2)S}\eta_{A(B)P-1}\nabla)\right]$$