Physica E 73 (2015) 250–256

Contents lists available at ScienceDirect

Physica E

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

Magnetic behaviors and multitransition temperatures in a nanoisland

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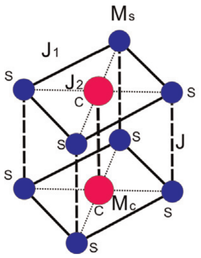
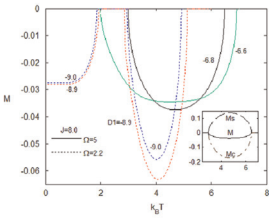
HIGHLIGHTS

- A nanoisland consists of a center spin-5/2 and perimeter spin-3/2 atoms.
- The general formula for the magnetization and internal energy is given.
- A new type reentrant phenomenon with multitransition temperatures is found.

GRAPHICAL ABSTRACT

A model of nanoland is constructured and multitransition temperatures are found in the system.





ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
23 May 2015
Accepted 25 May 2015
Available online 28 May 2015

Keywords:
Nanoisland
Single-ion anisotropy
Multitransition temperatures
Magnetization

ABSTRACT

A nanoisland consists of center spin-5/2 and perimeter spin-3/2 atoms, which is described by transverse Ising model with single-ion anisotropy. Magnetic behaviors of the nanoisland are studied by the effective-field theory with correlations and the differential operator technique. The formulas of the magnetization and the phase transition of the system are given. The numerical results of the phase transition, the magnetization, the initial susceptibility and the internal energy have been discussed. Some interesting phenomena, such as a new reentrant, are found. Namely there are multitransition temperatures dependent on competition among the single-ion anisotropies, the transverse field and the interlayer coupling. These results can provide some guidance to structure design in the nanoislands.

1. Introduction

Nanomaterials such as nanoisland, nanoparticle, nanowire, nanotube and so on have received wide attention because of their novel physical and chemical properties [1–5]. A large fraction of the atoms at the surface make their properties different with the matching bulk. Nanoisland as one of the nanomaterials can significantly improve the specific surface area. It may apply to solar cells with small structure and high coverage, lithium ion battery and photoelectric detectors. From both fundamental theoretical and experimental viewpoints, the novel and traditional properties combinations and nanostructures applications make the study of nanoisland an important issue. In experiments, nanoislands have been synthesized by various methods. GaN as a candidate for the blue light-emitting-diode has attracted great attention recently because of industrialization application and especially this year's Nobel Prize in physics. The nanostructure GaN can largely improve performing the blue light devices. An uniform GaN nano-pillars arrays has been successfully fabricated by Ni nano-island mask. *Ni* nanoisland is formed through the annealing under the ammonia. The size of the Ni islands depends on the original thickness of the nickel films. And nickel's thickness increases as the Ni film thickness increasing [6]. The self-organized iridium nanoislands are formed by an annealing after the deposition of Ir thin film on silicon substrate. The nanoislands have the shape of compressed half-spheres, whose height is between 30 nm and 100 nm in

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http://dx.doi.org/10.1016/j.physe.2015.05.028
1386-9477/

diameter [7]. Using repeated sputtering deposition and post-deposition annealing processes, gold nanoisland arrays with well growth are controlled [8]. An array of ferromagnetic nanoislands nondestructively has been patterned by a local phase transformation by low-energy proton irradiation. Such an array nanoisland is strong enough to overcome the so-called superparamagnetism limit in magnetic recording [9]. Porro et al. have investigated the magnetization reversal process of nanoislands by the magneto-optical Kerr effect. For certain directions of the applied field they have found the dipolar interaction of nanoislands affects the reversal process deeply [10]. Boltaev et al. have also studied the magnetization processes of multilayer structures consisting of periodically alternating island layers. The vortex-like magnetization of island is proposed. The results show the unidirectional axis of magnetization does not lead to exchange bias of hysteresis loops [11]. Co nanoislands on the Au (111) and Cu (111) surfaces have been investigated based on scanning tunneling microscopy and spectroscopy. The results indicated that Co nanoislands prefer to aggregate at the step edge and dislocation sites on the reconstructed Au (111) surface and at the step edge on the Cu (111) surface, respectively [12]. $La_{0.7}Sr_{0.3}MnO_3$ nanoislands show bulk-like average magnetic properties at Curie temperature and saturation magnetization. Magnetic force microscopy studies reveal the correlation between nanoisland size and its magnetic domain structure [13]. Borkovska et al. have studied photoluminescence and Raman scattering CdSe/ZnSe nanostructures. Both Stokes and anti-Stokes emission are observed by resonant excitation of Cd-containing nanoislands [14]. To prepare nanoisland has a breakthrough in the experiment, however, the relevant theoretical research is still lagging behind. Only a few researchers have carried out the theoretical study of nanoisland. For example, Young et al. have systematically studied the atomic structures and electronic properties for two-dimensional triangular ZnO nanoislands by first-principles calculations. The result shows the magnetism of the monolayer ZnO nanoisland resulting from the oxygen-edge states dependent on their sizes [15]. Kaneyoshi has studied the phase diagram and magnetizations of the nanoisland by using the effective field theory with correlations (EFT). Some characteristic are found which origin from the frustration induced by an interlayer coupling and two transverse fields [16,17]. However, the magnetic properties of nanoisland have not been investigated under the condition of coexistence transverse fields and magnetic anisotropy.

By the effective-field theory with correlations, we have successfully discussed the properties of nanoparticles, nanowires, nanotubes and nanoscale films in our previous work [18–23]. The exchange coupling, the single-ion anisotropy and the transverse field have play important roles in the magnetic properties of the nanomaterials, such as, magnetization and the phase diagrams. Also, experimental and theoretical results show the magnetic anisotropy has an important influence on magnetic properties of the low-dimension systems [24,25]. Here, the magnetic properties of the nanoisland will be studied by this theory (EFT). Particular emphasis is given to the effects of the surface anisotropy on them. For suitable values of the parameters, multi-transition temperatures may be obtained in the nanoisland. The paper is organized as follows. In Section 2, we briefly introduce the nanoisland described by the transverse Ising model with single-ion anisotropy. In Section 3, typical numerical results for the magnetizations, the initial susceptibility and the internal energy of the system are investigated in detail. Finally, Section 4 is devoted to the summary.

2. Formulations

A model of a nanoisland with square structure is plotted in Fig. 1. The small *S* and big balls *C* denote spin-3/2 and 5/2 magnetic atoms in the perimeter and the center of the nanoisland, respectively. Here only consider the first nearest-neighbor interactions between the sites. The exchange coupling is ferromagnetic $J1\ (>0)$ in the perimeter, and that is ferromagnetic $J\ (>0)$ between the upper and bottom. $J2\ (<0)$ is the ferrimagnetic exchange coupling between the perimeter and center. M_S and M_C represent the longitudinal magnetization of the magnetic atoms in the perimeter and the center, respectively.

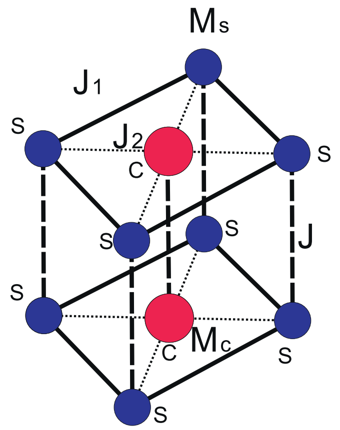

Fig. 1. Schematic of a ferrimagnetic nanoisland. The small *S* and big balls *C* delegate spin-3/2 and 5/2 magnetic atoms in the perimeter and the center, respectively. The solid lines represent the intralayer ferromagnetic exchange coupling *J*1. The dashed lines represent the interlayer ferromagnetic exchange coupling *J*. The dotted lines present the intralayer ferrimagnetic exchange coupling *J*2.

The Hamiltonian of the nanoisland considering the transverse field and anisotropy is given by

$$H = -J1\sum_{i,j}\sigma_i^z\sigma_j^z - J\sum_{i,k}\sigma_i^z\sigma_k^z - J\sum_{m,n}S_m^zS_n^z - J2\sum_{i,m}\sigma_i^zS_m^z - \Omega\left(\sum_i\sigma_i^x + \sum_m S_m^x\right) - D1\sum_i\left(\sigma_i^z\right)^2 - D2\sum_m\left(S_m^z\right)^2 - h\left(\sum_i\sigma_i^z + \sum_m S_m^z\right) \quad (1)$$

where σ_i^z and S_m^z are spin-3/2 and 5/2 from the perimeter and the center of the nanoisland, respectively. $D1$ and $D2$ are the single-ion anisotropies which comes from the perimeter and the center of the nanoisland, respectively. Ω and h represent the transverse and the longitudinal magnetic field, respectively. Supposing the initial spin values of σ_i^z and S_m^z are selected as $\sigma_i^z = 3/2$ and $S_m^z = -5/2$ for opposite direction. σ_i^z is along the positive direction of the longitudinal magnetic field. The value of $J2 = -1$ takes as a unit $|J2|$.

Based on the effective-field theory with correlations [16–23,26], we can get coupled equations of the longitudinal (transverse) magnetizations M_C (M_{Cx}) in the center and M_S (M_{Sx}) at the perimeter as follows:

$$M_c(M_{cx}, \eta_c^2) = \left[\cosh\left(J_2\eta_s\nabla\right) + \frac{M_s}{\eta_s}\sinh\left(J_2\eta_s\nabla\right)\right]^4 \times \left[\cosh\left(J\eta_c\nabla\right) + \frac{M_c}{\eta_c}\sinh\left(J\eta_c\nabla\right)\right] f_c(x)(k_c(x), g_c(x))|_{x=0} \quad (2)$$