Journal of Magnetism and Magnetic Materials 402 (2016) 196–199

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Comparison of the effect of the exchange and single-ion anisotropy on the magnetic properties of thin ferromagnetic films

Vladimir Ilkovič [1]

Bogoliubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Moscow region, Russia

ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form
1 October 2015
Accepted 25 October 2015
Available online 26 October 2015

Keywords:
Magnetic properties of thin films
Surfaces, and interfaces
Quantized spin model
Magnetic anisotropy
Spin wave

ABSTRACT

Using the many-body Green function theory, we caculate the magnetic reorientation temperature and the anisotropic parallel susceptibility of ferromagnetic Heisenberg thin films with the exchange and single-ion anisotropy. Particularly, we compare the effect of these anisotropies on the above mentioned observables. On the basis of our results, one cannot generally claim that these anisotropies are equivalent in the whole rangle of their parameters.

1. Introduction

Among the different experimental methods the measurement of the magnetic susceptibility is a very powerful method for the analysis of thin film systems. The parallel and transverse susceptibilities of ferromagnetic ultrathin cobalt films with in-plane exchange anisotropy were measured in [1]. The isotropic exchange interaction and the exchange anisotropy were determined by comparison with a theoretical analysis of the susceptibilities. In [2], the Green function theory was employed to calculate susceptibilities of ferromagnetic thin films with the exchange and single-ion anisotropy, respectively. We note, only one value of the strength of the exchange and single-ion anisotropy, respectively, was used in the calculation. The calculated values of these observables were, in this case, quantitatively so similar that it was unlikely that experimental measurements could decide on which type of anisotropy was acting in a real ferromagnetic film. This may appear somewhat surprising, since these anisotropies originate from very different physical mechanisms. The aim of our work is the investigation within the Green function theory of the magnetic reorientation temperature and the parallel susceptibility in the ferromagnetic thin films with the exchange and single-ion anisotropy in a wide range of their parameters.

2. Theory and fundamental equations

We consider a ferromagnetic thin film consisting of a superposition of L atomic planes (layers) of a square lattice (L is the thickness of the film). We start with following Hamiltonian:

$$H = -\frac{1}{2}\sum_{<jk>} J_{jk}\left(S_j^- S_k^+ + S_j^z S_k^z\right) - \frac{1}{2}D\sum_{<jk>} S_j^z S_k^z - K_2\sum_j (S_j^z)^2 - g\mu_B H^x \sum_j S_j^x - g\mu_B H^z \sum_j S_j^z. \quad (1)$$

Here the notation $S^{\pm}_{j(k)} = S^x_{j(k)} \pm \mathrm{i}S^y_{j(k)}$ is introduced and $<jk>$ indicates summation over the nearest neighboring lattice sites. The Hamiltonian consists of Heisenberg exchange interaction with strength $J > 0$ between the nearest neighboring lattice sites, an uniaxial in-plane exchange anisotropy in the z-direction with strength $D > 0$, a second-order in-plane single-ion anisotropy with strength $K_2 > 0$, an external transverse H^x and longitudinal H^z magnetic fields.

The applied Green function method in this work is based on transformation of the fixed coordinate system (x, y, z) into a local coordinate system (X, Y, Z). The Z-axis is set to be parallel to the z-component of the magnetization. Note that the new coordinate system is rotated by θ_μ in layer μ, where θ_μ is the angle between the z-axis and the magnetization in the layer μ. This theory was described in detail elsewhere [3] and [4]. A remarkable result of this theory is that the effective field aligned parallel to the Z-axis can be written as a sum of the external magnetic field and a single-ion effective anisotropy field:

E-mail address: vilko@theor.jinr.ru
[1] Permanent address: Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 040 01 Košice, Slovak Republic.

http://dx.doi.org/10.1016/j.jmmm.2015.10.094
0304-8853/

$$g\mu_B H_{ef} = g\mu_B H^x \sin\theta_\mu + g\mu_B H^z \cos\theta_\mu + 2K_2\langle S^Z\rangle Q^{(S)}\left[\cos^2\theta_\mu - \frac{1}{2}\sin^2\theta_\mu\right], \quad (2)$$

where $Q^{(S)} = 1 - [S(S+1) - \langle (S^Z)^2\rangle]/2S^2$. The rotation angle θ_μ is determined from the condition that the commutator of S^Z with the Hamiltonian vanishes in the rotated frame. In [3] and [4], the expression for the equilibrium angle θ_μ was derived:

$$-g\mu_B H^x + 2K_2\langle S^Z\rangle Q^{(S)} \sin\theta_\mu = 0 \quad (3)$$

Combining expression (2) with condition (3), we can write the components of the effective field in the fixed coordinate system as

$$g\mu_B H^x_{ef} = g\mu_B H^x - K_2\langle S^Z\rangle Q^{(S)}\sin^3\theta_\mu, \cdot$$
$$g\mu_B H^x_{ef} = g\mu_B H^z + 2K_2\langle S^Z\rangle Q^{(S)}\left(1 - \frac{1}{2}\sin^2\theta_\mu\right)\cos\theta_\mu. \quad (4)$$

The orientation angle θ_μ of the magnetization is determined by the components of the effective field $\tan\theta_\mu = g\mu_B H^x_{ef}/g\mu_B H^z_{ef}$.

In order to treat the magnetic properties of ferromagnetic thin films with spin $S = 1$, we need the following Green function in energy space $\tilde{G}^{(m)}_{jk}(\omega) = \langle\langle S^+_j; (S^Z_k)^m S^-_k\rangle\rangle_\omega$ defined in the local reference frame:

$$\tilde{G}^{(m)}_{jk}(\omega) = \langle\langle S^+_j; (S^Z_k)^m S^-_k\rangle\rangle_\omega, \; S^\pm_{j(k)} = S^X_{j(k)} \pm \mathrm{i}S^Y_{j(k)}, \quad (5)$$

where $m = 0, 1$. The equation of motion for the Green function $\tilde{G}^{(m)}_{jk}(\omega)$ is

$$\omega\tilde{G}^{(m)}_{jk}(\omega) = U^{(m)}_{jk}\delta_{jk} + \langle\langle [S^+_j, H]; (S^Z_k)^m S^-_k\rangle\rangle_\omega, \quad (6)$$

with the inhomogeneity

$$U^{(m)}_{jj} = \langle [S^+_j, (S^Z_j)^m S^-_j]\rangle = 2\langle (S^Z_j - 1)^m S^Z_j\rangle + \langle [(S^Z_j - 1)^m - (S^Z_j)^m][2 - S^Z_j - (S^Z_j)^2]\rangle. \quad (7)$$

For a ferromagnetic film because of the translation symmetry, the Green function $\tilde{G}^{(m)}_{jk}(\omega)$ and the inhomogeneity $U^{(m)}_{jj}$will depend only on the position μ of layers involved, so that $\tilde{G}^{(m)}_{jk}(\omega) = \tilde{G}^{(m)}_{\mu\nu}(\omega)$ and $U^{(m)}_{jj} = U^{(m)}_{\mu\mu}$. The higher-order Green functions in the set of equations of motion have to be decoupled to obtain a closed set of equations of motion. We combine the usual random phase approximation for the Green function that appearing in the nonlocal exchange term and a generalized Anderson-Callen approximation, developed in [3], in the local anisotropy term.

After a two-dimensional Fourier transform to momentum space one obtains the resulting equations of motion for the Green function $G^{(m)}_{\mu\nu}(\Omega, \boldsymbol{q}) = J\tilde{G}^{(m)}_{\mu\nu}(\Omega, \boldsymbol{q})$ (where $\Omega = \omega/J$), which can be written for the film with thickness $L = 3$ ($\mu(\nu) = 1, 2, 3$) in the matrix form

$$\Delta(\Omega)\boldsymbol{G}^{(m)}_\mu(\Omega, \boldsymbol{q}) = \boldsymbol{U}^{(m)}_\mu \quad (8)$$

with

$$\boldsymbol{G}^{(m)}_\mu(\Omega, \boldsymbol{q}) = \begin{pmatrix} G^{(m)}_{1,\mu}(\Omega, \boldsymbol{q}) \\ G^{(m)}_{2,\mu}(\Omega, \boldsymbol{q}) \\ G^{(m)}_{3,\mu}(\Omega, \boldsymbol{q}) \end{pmatrix}, \; \boldsymbol{U}^{(m)}_\mu = \begin{pmatrix} U^{(m)}_{1,\mu}\delta_{1,\mu} \\ U^{(m)}_{2,\mu}\delta_{2,\mu} \\ U^{(m)}_{3,\mu}\delta_{3,\mu} \end{pmatrix}, \quad (9)$$

$$\Delta(\Omega) = \begin{pmatrix} \Omega - A_1 & B_1 & 0 \\ B_2 & \Omega - A_2 & B_2 \\ 0 & B_3 & \Omega - A_3 \end{pmatrix}, \quad (10)$$

We assume that both surfaces of the thin layers are symmetrical, i.e. valid $A_3 = A_1$, $B_3 = B_1$ and A_μ, B_μ (for $\mu = 1, 2$) are given as follows:

$$A_1 = \langle S^Z_1\rangle[4 - \gamma_{\boldsymbol{q}} + 4d] + h^x \sin\theta_1 + h^z\cos\theta_1 + k_2\langle S^Z_1\rangle Q^{(1)}_1(\cos^2\theta_1 - \frac{1}{2}\sin^2\theta_1) + \langle S^Z_2\rangle(1 + d) \quad (11)$$

$$A_2 = \langle S^Z_2\rangle[4 - \gamma_{\boldsymbol{q}} + 4d] + h^x \sin\theta_2 + h^z\cos\theta_2 + k_2\langle S^Z_2\rangle\tilde{Q}^{(1)}_2(\cos^2\theta_2 - \frac{1}{2}\sin^2\theta_2) + 2\langle S^Z_1\rangle(1 + d), \quad (12)$$

$$B_\mu = \langle S^Z_\mu\rangle, \quad (13)$$

and

$\gamma_{\boldsymbol{q}} = 2[\cos(q_x) + \cos(q_y)]$, $h^x = g\mu_B H^x/J$, $h^z = g\mu_B H^z/J$, $\langle S^Z_3\rangle = \langle S^Z_1\rangle$, - $k_2 = K_2/J$, $d = D/J$.

The spin-wave spectrum Ω_i is obtained by solving the secular equation: $\det\Delta(\Omega) = 0$. From (8) one obtains

$$\boldsymbol{G}^{(m)}_{\mu\mu}(\Omega, \boldsymbol{q}) = U^{(m)}_{\mu\mu}\sum_{i=1}^{3}\frac{R_{\mu\mu}(\Omega_i, \boldsymbol{q})}{\Omega - \Omega_i} \quad (14)$$

where $R_{\mu\mu}(\Omega_i, \boldsymbol{q}) = \Delta_{\mu\mu}(\Omega_i)/\prod_{j\neq i}(\Omega_i - \Omega_j)$ and $\Delta_{\mu\mu}(\Omega_i)$ is obtained from determinant $\Delta(\Omega_i)$ by omitting the first row and first column ($\mu = 1$) or second row and second column ($\mu = 2$). After using the spectral theorem we finally obtain the correlation function for the layers $\mu = 1$ and $\mu = 2$:

$$\langle (S^Z_\mu)^m S^-_\mu S^+_\mu\rangle = U^{(m)}_{\mu\mu}\Phi_\mu \quad (15)$$

where

$$\Phi_\mu = \frac{1}{\pi^2}\int_0^\pi\int_0^\pi dq_x dq_y \sum_{i=1}^{3}\frac{\Delta_{\mu\mu}(\Omega_i)}{\prod_{j\neq i}(\Omega_i - \Omega_j)}\frac{1}{e^{\Omega_i/kT} - 1}, \quad (16)$$

$$\langle (S^Z_\mu)^m S^-_\mu S^+_\mu\rangle = 2\langle (S^Z_\mu)^m\rangle - \langle (S^Z_\mu)^{m+1}\rangle - \langle (S^Z_\mu)^{m+2}\rangle \quad (17)$$

We obtain from (8), (15) and (17) with $m = 0$ and $m = 1$ the equations for magnetization $\langle S^Z_\mu\rangle$ and second moment $\langle (S^Z_\mu)^2\rangle$:

$$\langle S^Z_\mu\rangle = \frac{1 + 2\Phi_\mu}{1 + 3\Phi_\mu + 3\Phi^2_\mu}, \; \langle (S^Z_\mu)^2\rangle = \frac{1 + 2\Phi_\mu + 2\Phi^2_\mu}{1 + 3\Phi_\mu + 3\Phi^2_\mu}. \quad (18)$$

Eq. (18) have to be solved numerically in order to obtain $\langle S^Z_\mu\rangle$ and $\langle (S^Z_\mu)^2\rangle$. Since $\langle S^Z_\mu\rangle$ depends on the magnetizations of the other layers via Ω_i, we have to solve self-consistently the set of Eq. (18) written for all layers, to obtain magnetizations of all layer magnetizations at the temperature T. The components of the magnetization in the fixed system (x, y, z) can be calculated from the following equations:

$$\langle S^z_\mu\rangle = \langle S^Z_\mu\rangle\cos\theta_\mu, \; \langle S^x_\mu\rangle = \langle S^Z_\mu\rangle\sin\theta_\mu \quad (19)$$

The susceptibility χ^{zz}_μ along the easy axis will be determined numerically as differential quotient

$$\chi^{zz}_\mu = \left(\langle S^z_\mu(h^z)\rangle - \langle S^z_\mu(0)\rangle\right)/h^z. \quad (20)$$

3. Results

The reorientation temperature $T_{R\mu}$ of the layer μ is defined as the temperature where the longitudinal magnetization $M^z_\mu \equiv \langle S^z_\mu\rangle$ vanishes; the transverse magnetization $M^x_\mu \equiv \langle S^x_\mu\rangle$ is not zero and the equilibrium orientation angle $\theta_\mu = 90^o$. By performing numerical integrations in (18) and using (19) we can estimate the