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Spin Wave Characteristics of Inhomogeneous Ferromagnetic Layered Composites

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A ferromagnetic layered composite ABAB. . . ABA with nonuniform distribution of anisotropy parameter is studied. The effects of damping leading to non-zero line-width of ferromagnetic resonance peaks are also taken into account. As a result the dependence of spin wave parameter B and resonance line-width on parameters characterizing system under consideration were obtained for the case of uniform anisotropy parameter and for quadratic distribution of this parameter in magnetic layers, respectively.

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1. Introduction

Periodic composite magnetic materials have increased interest in the areas of magnetism and spintronic devices, due to their potential application to data-processing equipment [1–3]. Therefore it is important to know the properties of spin waves to minimize their disturbing influence or make use of them in logic devices. Theoretical and experimental approaches dedicated to periodic composite magnetic materials showed that in description of their properties it is necessary to take into account the anisotropic factors. Recently, theoretical and experimental approaches dedicated to layered systems showed the role of the anisotropic factors is very important for proper description of their properties [4, 5]. The aim of presented paper is to calculate spin wave resonance spectrum characteristics for multilayered system with spatial distribution of anisotropy across magnetic layers.

2. Method and calculations

We consider a ferromagnetic layered composite ABAB. . . ABA, where A and B are different homogeneous ferromagnetic materials and each block A is made of N_{A} layers and each block B is made of N_{B} layers. We assume that an externally applied static magnetic field of the strength in the range corresponding to the ferromagnetic resonance condition is oriented perpendicularly to the external surface of the system and all the spins can be considered statically as parallel to the external field. We focus our attention on the exchange modes that can be separated from the magnetostatic ones by the proper choice of radiofrequencies. The system under considerations is constructed of p of AB blocks and is described by the Heisenberg Hamiltonian consisting of the exchange, anisotropy, and Zeeman terms, respectively.

The anisotropy parameter connected with the atomic plane ν is the sum of the uniaxial volume anisotropy parameter D along the preferential axis and the anisotropy D_i at the surface between A and B sublayers and the surface anisotropies at the surface belonging to the block A (D_{S1}) and B (D_{S2}), respectively. We introduce the additional term $D_{v'}$ depending on the position inside the magnetic layer, which after [5] is assumed in the quadratic form

$$D_{\nu'} = D_0 \left(1 - \frac{\varepsilon \nu'^2}{N_j^2}\right), \tag{1}$$

where ε denotes the magnetic distortion parameter defining the profile of magnetic anisotropy and $-N_j/2 \le \nu' \le N_j/2$ and j = A,B, respectively. Then a set of equations for coefficients $b_\nu(k_i)$ describing amplitudes of spin waves with wave vectors k_i [6] can be written in the following form:

$$\left[\frac{D_{S1} + D_{v'}}{A_1} - \alpha(k_i)\right] b_1(k_i) + b_2(k_i) = 0,$$

$$\ldots$$

$$b_{v-1}(k_i) - \left[\frac{D_{\nu'}}{A_1} - \alpha(k_i)\right] b_v(k_i) + b_{v+1}(k_i) = 0,$$

$$\ldots$$

$$b_{N_{\mathrm{A}}-1}(k_i) - \left[\frac{D_i + D_{v'}}{A_1} - \alpha(k_i)\right] b_{N_{\mathrm{A}}}(k_i) + \frac{A_{12}}{A_1} b_{N_{\mathrm{A}}+1}(k_i) = 0,$$

$$\frac{A_{12}}{A_2} b_{N_{\mathrm{A}}-1}(k_i) - \left[\frac{D_i + D_{v'}}{A_2} - \alpha(k_i)\right] b_{N_{\mathrm{A}}+1}(k_i) + b_{N_{\mathrm{A}}+2}(k_i) = 0,$$

$$\ldots$$

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$$b_{N_A+v-1}(k_i) - \left[\frac{D_{\nu'}}{A_1} - \alpha(k_i)\right] b_{N+v}(k_i)$$
$$+ b_{N_A+v+1}(k_i) = 0,$$

...

$$b_{p(N_A+N_B)-1}(k_i)$$
$$- \left[\frac{D_{S2}+D_{v'}}{A_2} - \alpha(k_i)\right] b_{p(N_A+N_B)}(k_i) = 0. \qquad (2)$$

In Eq. (2) A_1 and A_2 denote the exchange integrals for sublayers A and B, respectively, while A_{12} stands for the parameter of exchange interaction between spins belonging to interface layers in different magnetic sublayers. We use the transfer matrix method [7, 8] which allows one to find wave vectors k_i of elementary magnetic excitations ($i = 1 \ldots p(N+M)$) and introduce the matrix $\hat{W}$:

$$\hat{W} = \prod_{\nu=1}^{p(N+M)} \hat{T}_\nu, \qquad (3)$$

with the following 2×2 matrices defined as:

$$\hat{T}_\nu = \begin{pmatrix} 2+\alpha_\nu(k_i) & -\frac{D_{\nu'}}{A_j} \\ \frac{D_{\nu'}}{A_j} & 0 \end{pmatrix}, \qquad (4)$$

for ν belonging to the internal layers of A and B subsystems. For the interface region the matrices are of the following form [9]:

$$\hat{T}_{N_A} = \begin{pmatrix} 2+\alpha_{N_A}(k_i) & -\frac{A_{12}+D_{N_A}}{A_1} \\ 1 & 0 \end{pmatrix},$$

$$\hat{T}_{N_A+1} = \begin{pmatrix} 2+\alpha_{N_A+1}(k_i) & -\frac{A_{12}+D_{N_A+1}}{A_2} \\ 1 & 0 \end{pmatrix},$$

$$\hat{T}_{N_B+1} = \begin{pmatrix} 2+\alpha_{N_B+1}(k_i) & -\frac{A_{12}+D_{N_B+1}}{A_1} \\ 1 & 0 \end{pmatrix}. \qquad (5)$$

In order to find magnon wave vectors k_i the energy dependent terms $\alpha_\nu(k_i)$ from Eq. (2) have to be determined. The profiles of elementary magnetic excitations can be calculated by solving the characteristic equation (3) involving boundary conditions at external surfaces, namely

$$\begin{pmatrix} 1 & \frac{2\alpha_1+D_{S_1}-1}{2-2\alpha_1-D_{S_1}} \end{pmatrix} \hat{W} \begin{pmatrix} 1 \\ \frac{2\alpha_{p(N_A+N_B)}+D_{S_2}-1}{2-2\alpha_{p(N_A+N_B)}-D_{S_2}} \end{pmatrix} = 0. \qquad (6)$$

Magnetisation of the system and its temperature dependence can be then obtained [10]. We have calculated the spin wave parameter B describing decrease of spontaneous magnetisation $M(T)$ of the considered system with temperature as a result of magnon excitation in low temperature region given by the Bloch law as

$$M(T) = M_0\left(1 - BT^{3/2}\right). \qquad (7)$$

The parameter B has been calculated for the case of uniform (u.a.) and for the case of anisotropy distribution given by Eq. (1) (a.d.) in dependence of the thickness of the system and of the filling fraction defined as [11]:

$$f = \frac{N_A}{N_A + N_B}. \qquad (8)$$

Results obtained in our calculation with $D_{S1}/A_1 = D_{S2}/A_2$ =0,1 are presented in Figs. 1 and 2.

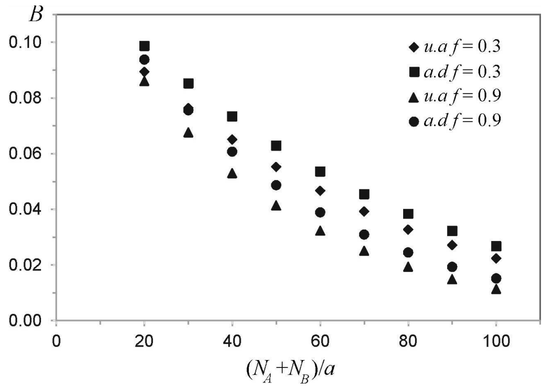

Fig. 1. The dependence of spin wave parameter B on the thickness of block AB for two filling fractions f and for uniform (u.a.) and position dependent (a.d.) anisotropy parameter, respectively.

The spin wave parameter increases for non-uniform distribution of anisotropy parameter in comparison to results obtained for uniform one. Similar effect have been reported when existence of various sources of imperfection e.g. roughness in surface and interface region have been taken into account [9, 14].

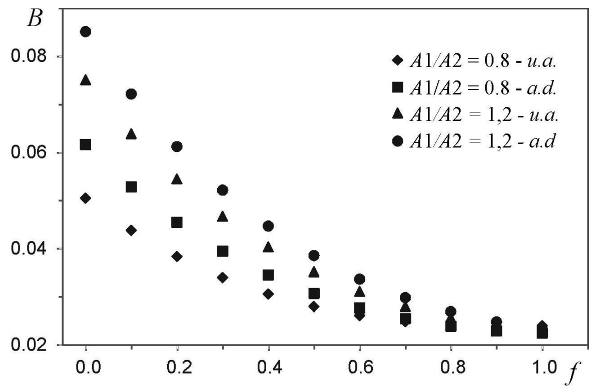

Fig. 2. The dependence of spin wave parameter B on the filling fraction f for two ratios of exchange integrals and for uniform (u.a.) and position dependent (a.d.) anisotropy parameter, respectively.

Formalism based on the Green function method presented above has been extended by introducing damping effects due to magnon–magnon interaction [13]. The spin wave characteristics can be then calculated employing the relaxation equation [14] including the damping term derived on the basis of results of Wesselinowa [15, 16]. As a result the distribution of resonance intensity in ferromagnetic resonance (FMR) has been obtained giving resonance spectra with the shape depending on the filling fraction and interaction parameters with non-zero line-width of resonance lines. The results presented in this paper show that introducing damping effect even on the basis of phenomenological relaxation equation gives possibility of calculating of resonance spectra with non-zero line-width. Figure 3 gives an example of dependence of line-width of the line of highest intensity on filling parameter.

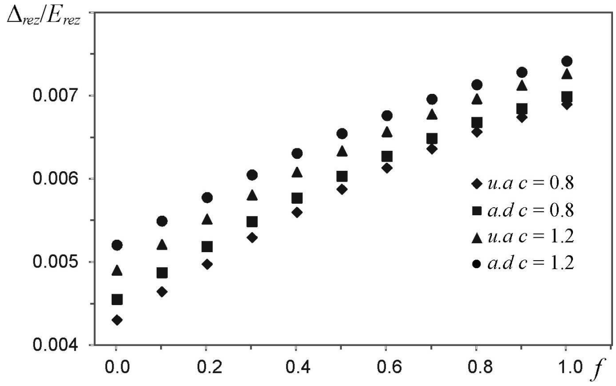

Fig. 3. The dependence of relative line-width of the first resonance peak (normalized to resonance energy) on the filling fraction for two ratios of exchange integrals and for uniform (u.a.) and position dependent (a.d.) anisotropy parameter, respectively.

Taking into account the anisotropy distribution given by Eq. (1) leads to relative broadening of resonance peaks in comparison to the systems with uniform anisotropy. The difference between values obtained for both situations is not very significant, however characteristics for (u.a.) and (a.d.) can be easily distinguished in Fig. 3.

The results obtained show that in the frames of the model used in this work deviation of the anisotropy parameter from uniform distribution influences basic characteristics of spin wave resonance spectra. Very similar curves to that presented in Figs. 1–3 can be obtained taking into account exponential distribution of anisotropy parameter proposed in [5].

4. Conclusions

It has been shown that taking into account distribution of anisotropy across the layer can help to explain experimental results [5] obtained in spin wave resonance. Calculations presented in this paper are an attempt to investigate of spin waves in materials with non-uniform anisotropy by modification of the Green function method used to study of magnetic properties of multilayers. The results obtained which are only of qualitative character show that introducing of anisotropy distribution across magnetic layers in magnetic composites leads to change of the wave parameter B and the changes of resonance spectra. These changes are similar to the behaviour caused by the existence of another source of non-homogeneity, namely the existence of roughness in the region of surface and interface.

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