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Low Temperature Properties of Inhomogeneous Magnetic Multilayers

A. Urbaniak-Kucharczyk*
Faculty of Physics and Applied Informatics, University of Łódź, Pomorska 149/153, 90-236 Łódź, Poland

System of two magnetic layers with nonuniform distribution of anisotropy parameter and exchange coupled by nonmagnetic spacer is studied by means of the Green function approach. Our attention is focussed on the elementary excitations and low temperature magnetisation behavior. The spin wave parameter B in the Bloch law $T^{3/2}$ is found as an oscillatory function of a spacer thickness. 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 resonance line-width on parameters characterizing system under consideration is 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

Research on magnetic ultrathin metallic films exchange coupled by nonmagnetic spacer has been growing considerably in last two decades due to increasing ability to produce samples of controlled quality and their technical importance (see e.g. [1, 2]). Basic magnetic properties of multilayer systems have been examined both by experimentalists and theoreticians; in particular, the problem of elementary magnetic excitations in multilayers has been considered in many papers, where magnon dispersion relation and parameters of spin wave spectra have been obtained (see e.g. [3–7]). Recently, theoretical and experimental approaches dedicated to layered systems showed that the role of the anisotropic factors is very important for proper description of their properties [8, 9]. 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 system consisting of two homogeneous ferromagnetic thin layers exchange coupled by a nonmagnetic spacer. The thicknesses of each layer are equal to N monatomic planes. To avoid the problem connected with detailed magnetic structure and rearrangement [3] 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 film surface 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 effective field H_{eff} acting on a spin is taken as a sum of the external uniform field, the demagnetising field, and the uniaxial bulk anisotropy field. The system under considerations was described by Heisenberg Hamiltonian consisting of the exchange, anisotropy, and Zeeman terms. The exchange interaction parameters between the spin plane ν and ν' are defined as:

$$J_{v,v'}=\begin{cases} J \text{ for } \nu,\, \nu' \in (1,\, N-1) \text{ and } (N+2,\, 2N) \\ J_{12} \text{ for } \nu,\, \nu'=N,\, N+1, \end{cases} \quad (1)$$

where J is the exchange integral homogeneous inside each of the magnetic layers while J_{12} stands for the parameter of indirect exchange interaction through nonmagnetic spacer between spins belonging to interface layers in different magnetic sublayers. The anisotropy parameter $A_{\nu\nu'}$ consists of the uniaxial volume anisotropy parameter A along the preferential axis, and the surface $A_s$and interface A_I anisotropy constants and the term $A_v$depending on the position inside the magnetic layer, namely

$$A_{vv,}=A+A_\nu+A_I\delta_{N,N+1}+A_{S_1}\delta_{1,2}+A_{S_2}\delta_{2N-1,2N}, \quad (2)$$

where after [9] the quadratic dependence of A_v on ν is assumed in the form

$$A_\nu = A_0\left(1-\frac{\varepsilon\nu^2}{N^2}\right), \quad (3)$$

where ε denotes the magnetic distortion parameter defining the profile of magnetic anisotropy and $-N/2 \le \nu \le N/2$.

In order to calculate the low magnetic properties of the system it is convenient to apply the Green function method in random phase approximation (RPA) [5, 6]. Within this method the transfer matrix $\hat{W}$ which allows to find wave vectors k_i of elementary magnetic excitations $(i = 1 \ldots 2N)$ can be used

$$\hat{W} = \prod_{\nu=1}^{2N} \hat{T}_\nu \quad (4)$$

with the following 2×2 matrices defined as [10]:

$$\hat{T}_\nu = \begin{pmatrix} 2+\alpha_\nu\,(k_i) & -\frac{A_\nu}{J} \\ \frac{A_\nu}{J} & 0 \end{pmatrix}, \quad (5)$$

*corresponding author; e-mail: aurbaniak@uni.lodz.pl

for $\nu \in (1, N-1)$ and $\nu \in (N-2, 2N)$. For the interface region

$$\hat{T}_N = \begin{pmatrix} 2+\alpha_N(k_i) & -\frac{J_{12}+A_N}{J} \\ 1 & 0 \end{pmatrix};$$

$$\hat{T}_{2N+1} = \begin{pmatrix} 2+\alpha_{2N+1}(k_i) & -\frac{J_{12}+A_{2N+1}}{J} \\ 1 & 0 \end{pmatrix}. \quad (6)$$

In Eqs. (5),(6) $\alpha_\nu(k_i)$ denotes the energy dependent term which has to be found in order to determine magnon wave vectors.

The spin wave mode profiles can be calculated by solving the characteristic Eq. (4) involving boundary conditions at external surfaces in the following form:

$$\begin{pmatrix} 1 & \frac{2\alpha_1+A_{S_1}-1}{2-2\alpha_1-A_{S_1}} \end{pmatrix} \hat{W} \begin{pmatrix} 1 \\ \frac{2\alpha_{2N}+A_{S_2}-1}{2-2\alpha_{2N}-A_{S_2}} \end{pmatrix} = 0. \quad (7)$$

Magnetisation of the system and its temperature dependence can be then obtained [11]. We focus our attention on spin wave parameter B describing decrease of total spontaneous magnetisation $M(T)$ with temperature as a result of magnon excitation in low temperature region. This decrease is given by Bloch's law, namely

$$M(T) = M_0 \left(1 - BT^{3/2}\right). \quad (8)$$

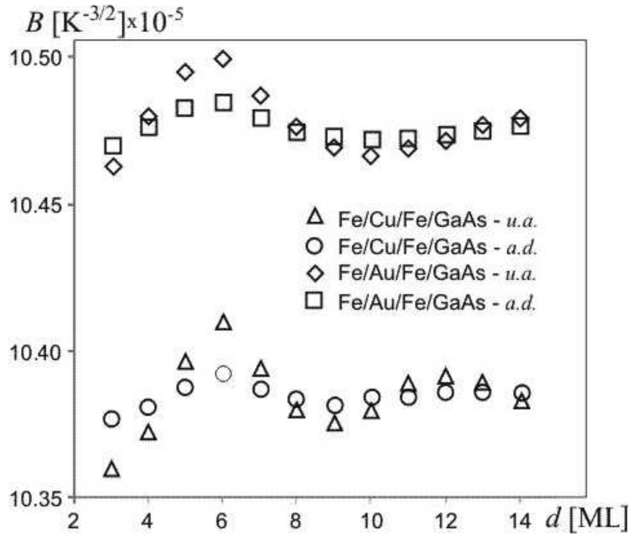

Fig. 1. The dependence of spin wave parameter B on the thickness of nonmagnetic spacer d for uniform ($u.a.$) and position dependent ($a.d.$) anisotropy parameter, respectively.

The numerical calculations based on the presented method have been carried out for the exchange coupled bilayer with the use of anisotropy parameters for the systems Fe/Cu/Fe/GaAs and Fe/Au/Fe/GaAs [12].

The results obtained for parameter B both for the case of position dependent anisotropy parameter ($a.d.$) and for uniform anisotropy ($u.a.$) are presented in Fig. 1. In agreement with [13] the parameter B shows oscillating behavior with period of oscillation of interlayer exchange parameter J_{12}. The amplitude of oscillation decreases for non-uniform distribution of anisotropy parameter. Similar effect can be obtained when existence of roughness in surface and interface region is taken into account [13].

The method applied above can be modified [6] by introducing damping effects due to magnon–magnon interaction [14] calculated on the basis of relaxation equation [15] including the damping term derived on the basis of results of Wesselinowa [16]. As a result a continuous distribution of resonance intensity in ferromagnetic resonance (FMR) has been calculated giving resonance spectra with non-zero line-width. The shape of this spectrum depends on the structure of the multilayer and interaction parameters. Figures 2–4 show the dependence of the line width of the first resonance line on the system parameters: its thickness and interlayer exchange coupling both for ferromagnetic and antiferromagnetic character of interlayer exchange coupling.

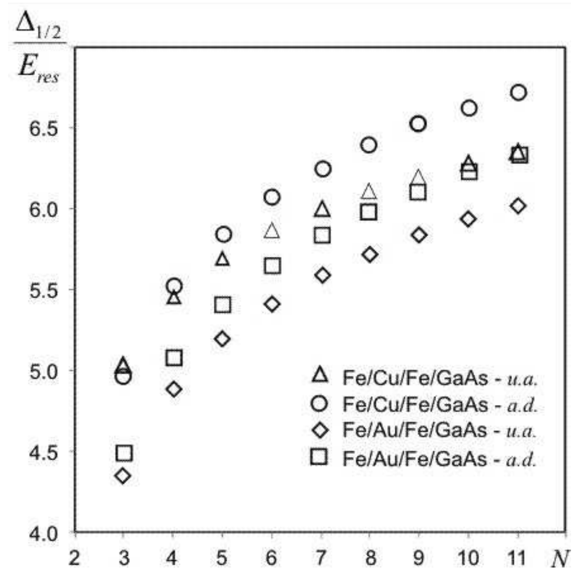

Fig. 2. The dependence of relative line-width of the first resonance peak (normalized to resonance energy) on the thickness of magnetic layer for ferromagnetically coupled bilayer for uniform ($u.a.$) and position dependent ($a.d.$) anisotropy parameter, respectively. $J_{12}/J = 0.25$.

Introduction of anisotropy distribution leads to relative broadening of resonance peaks in comparison to the systems with uniform anisotropy. One could not expect the difference between values obtained for both situations to be very significant, however characteristics for ($u.a.$) and ($a.d.$) can be easily distinguished in Figs. 2–4.

The results obtained show that in the frame the model used in this work deviation of the anisotropy parameter from uniform distribution influence basics characteristics of spin wave resonance spectra. Very similar curves to that presented in Figs. 2–4 can be obtained taking into account exponential distribution of anisotropy parameter proposed in [9].

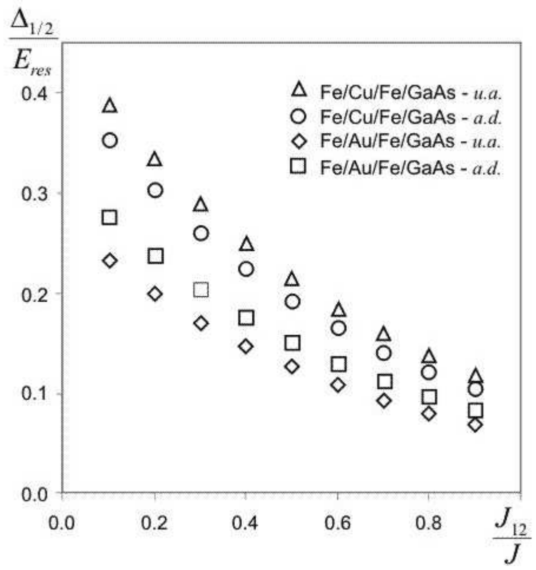

Fig. 3. The dependence of relative line-width of the first resonance peak (normalized to resonance energy) on the reduced interlayer exchange parameter for ferromagnetically coupled bilayer of thickness $2N = 8$ for uniform (*u.a.*) and position dependent (*a.d.*) anisotropy parameter, respectively.

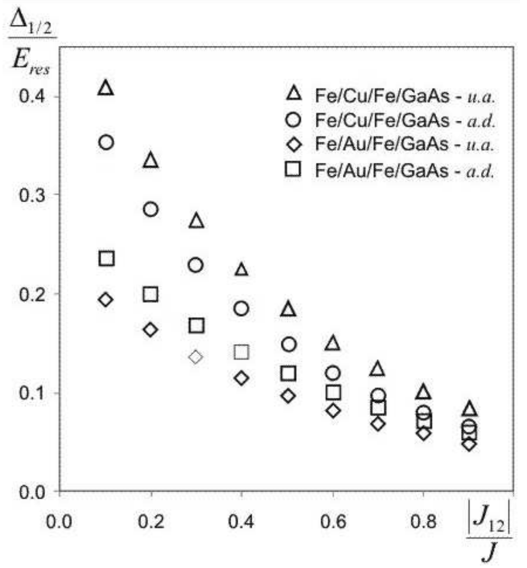

Fig. 4. The dependence of relative line-width of the first resonance peak (normalized to resonance energy) on the reduced interlayer exchange parameter for antiferromagnetically coupled bilayer of thickness $2N = 10$ for uniform (*u.a.*) and position dependent (*a.d.*) anisotropy parameter, respectively.

3. Conclusions

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 used to study of magnetic properties of multilayers. The results obtained which are only of qualitative character show that introducing of anisotropy distribution across very thin magnetic layers leads to change of the wave parameter B and the changes of resonance spectra similar to the behaviour caused by the existence of another source of non-homogeneity, namely the existence of roughness.

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