Journal of Magnetism and Magnetic Materials 419 (2016) 512–516

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

The resonance susceptibility of two-layer exchange-coupled ferromagnetic film with a combined uniaxial and cubic anisotropy in the layers

N.V. Shul'ga*, R.A. Doroshenko

Institute of Molecule and Crystal Physics, Academy of Sciences, 151, prospect Octobrya, Ufa 450075, Russia

ARTICLE INFO

Article history:
Received 9 April 2016
Received in revised form
23 June 2016
Accepted 23 June 2016
Available online 24 June 2016

Keywords:
Ferromagnetic resonance (FMR)
Two-layer film
Dynamic susceptibility

ABSTRACT

A numerical investigation of the resonance dynamic susceptibility of ferromagnetic exchange-coupled two-layer films with a combined cubic and uniaxial magnetic anisotropy of the layers has been performed. It has been found that the presence of cubic anisotropy leads to the fact that much of the off-diagonal components of the dynamic susceptibility are nonzero. The change of the ferromagnetic resonance frequencies and dynamic susceptibility upon the magnetization along the [100], [010], and [011] directions have been calculated. The evolution of the profile of the dynamic susceptibility occurring during the magnetization has been described. The impact of changes in the distribution of equilibrium and dynamic components of the magnetization on the dependences of the components of the dynamic susceptibility and the ferromagnetic resonance frequency on the external magnetic fields has been discussed.

1. Introduction

Experimental and theoretical investigation in the field of magnonics causes an increasing interest in the study of multilayered structures [1,2]. This is due to the fact that structures with a periodic modulation of magnetic parameters give unprecedented control of spin waves. Multilayered yttrium-iron garnet (YIG) films are an interesting object of study largely due to their uniquely low magnetic damping [3].

The theory of ferromagnetic resonance for a film consisting of exchange-coupled ferromagnetic layers was developed in the phenomenological approach in the papers [4–12]. It has been described that two-layer film has two ferromagnetic resonance modes, between which there is an energy gap. These calculations are usually carried out in the ultrathin layers approximation or it is supposed that the external magnetic field is high enough for a film in the ground state to be magnetized uniformly [12].

The ferromagnetic resonance (FMR) remains the technique of choice to investigate the parameters of multilayered films [10,13]. Upon excitation of the resonance by uniform alternating magnetic field in two-layer film, two FMR lines, and a series of spin-wave resonance (SWR) lines between them were observed [14]. The SWR series is due to the reflection of spin waves on the boundary of one of the layers. The number of SWR modes depends on the direction of the external magnetic field and the thickness of the layers of film [15].

The method suggested in [16] and based on the numerical calculation of the dynamic susceptibility makes it possible to study FMR frequencies in two-layer ferromagnetic films when the external magnetic field varies within wide limits. Since this method does not a priori postulate any shape of the coordinate dependence of variable components of magnetization, it become possible to study profiles of the FMR and SWR modes (the distribution of the dynamic susceptibility over the thickness). This method was used for the study of high-frequency properties a ferromagnetic film with the easy-plane and easy-axis anisotropy of the layers. It has been shown that at the nonzero parameter of the interlayer exchange interaction the dynamic components of the magnetization upon the ferromagnetic resonance are distributed through the film thickness inhomogeneously [17]. The evolution profiles of the of the FMR and SWR modes upon the changes in the strength [17] or in the direction of the external magnetic field for different thicknesses of the layers of film [18] has been described. Further, this method has been generalized to the case of ferromagnetic films with a combined cubic and uniaxial magnetic anisotropy of layers [19]. Further studies have shown that not only some features of dependences of the FMR frequencies on the field may indicate the changes taking place in the distribution of equilibrium and dynamic component of the magnetization. These changes can be judged by dependences of the integrated dynamic susceptibility

* Correspondence to: IFMK, 151, prospect Oktyabrya, Ufa 450075, Russia.
E-mail address: shulga@anrb.ru (N.V. Shul'ga).

http://dx.doi.org/10.1016/j.jmmm.2016.06.054
0304-8853/

on the field. This topic is the subject of our article. We present the results of numerical studies of the high-frequency properties of a two-layer film whose parameters are close to a two-layer YIG film.

2. Model

We consider two-layer exchange-coupled ferromagnetic film in an external magnetic field $\boldsymbol{H}$. The geometry of the film is shown in Fig. 1. The layers of the film have uniaxial anisotropy of various signs and identical cubic anisotropy. The thicknesses of the layers d_i, $i=1$, 2 are finite. The normal to the film coincides with the coordinate $\boldsymbol{OX}$ axis, and also with the axis [100] of the crystal and with the axis of uniaxial anisotropy. The direction of the magnetization $\boldsymbol{M}$ is characterized by a polar angle θ, which is counted off from the [001] axis of the crystal coinciding with $\boldsymbol{OZ}$ axis, and by an azimuthal angle ϕ, which is counted off from $\boldsymbol{OX}$ axis. The direction of the magnetic field $\boldsymbol{H}$ is characterized by a polar angle θ_h and by an azimuthal angle ϕ_h. It is assumed that the direction of the magnetization depends only on the coordinate x, and in the plane of the film the magnetization is distributed uniformly.

The functional of the energy of the system includes the energy of cubic anisotropy, the energy of uniaxial magnetic anisotropy of the easy plane and easy axis types, the Zeeman energy, the energy of exchange interaction inside the layers and the energy of interlayer exchange interaction as follows:

$$W = \sum_{i=1}^{2}\int_{V_i} dV\Big(\frac{K_1}{M_i^4}\Big\{\boldsymbol{M}_{x,i}^2\boldsymbol{M}_{y,i}^2 + \boldsymbol{M}_{x,i}^2\boldsymbol{M}_{z,i}^2 + \boldsymbol{M}_{z,i}^2\boldsymbol{M}_{y,i}^2\Big\} - \frac{K_{u,i}^*}{M_i^2}\boldsymbol{M}_{x,i}^2 -$$

$$-\boldsymbol{M}_i\boldsymbol{H} + \frac{\alpha_i}{2M_i^2}\big(\partial\boldsymbol{M}_i/\partial x\big)^2\Big) - \int_S \frac{J}{M_1M_2}\boldsymbol{M}_1\boldsymbol{M}_2 dS.$$

where K_1 is the first constant of cubic anisotropy, M_i are the saturation magnetizations of layers, $K_{u,i}^* = K_{u,i} - 2\pi M_i^2$ are the efficient constants of magnetic anisotropy taking into account a demagnetizing influence of the surface of layers, α_i are the constants of exchange interaction; and J is the constant of interlayer exchange interaction.

The problem was solved numerically. The procedure of the solution is described here only briefly; it was considered in more detail in [16–19]. Each layer of the film is divided into uniformly magnetized flat cells. The magnetization of the cell with the number l is designated as $\boldsymbol{m_l}$. Thus, the energy functional is converted into the sum of the energies of these cells. Minimizing the energy by standard methods of multidimensional minimization [20], we obtain an equilibrium distribution of the magnetization in the two-layer film. The dynamics of the magnetization in each cell is described by a set of Landau–Lifshitz equations. By linearizing the obtained set of equations relative to small deviations of the vectors of magnetization of the cells from their equilibrium direction $\delta\boldsymbol{m}_l$, we reduce the problem of obtaining the natural frequencies of the film to the solution of the generalized problem of eigenvalues for the thus-obtained set of linear equations. When calculating the dynamic susceptibility, a term of the form $\delta\boldsymbol{m}_l\boldsymbol{h}$

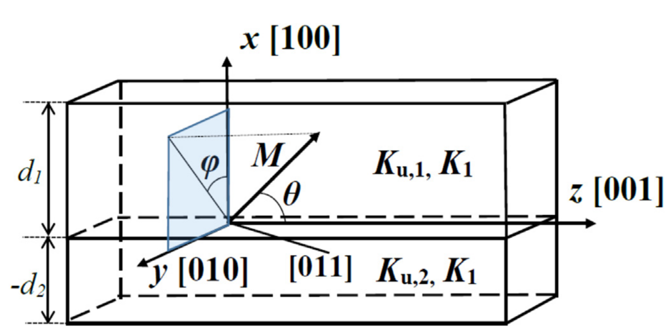

Fig. 1. Coordinate system.

where $\boldsymbol{h}$ is the ac magnetic field, is added into the energy of the system. A relaxation term in the Gilbert form [21] is added to the set of Landau–Lifshitz equations. The solution of the set of equations obtained after the linearization yields the dynamic components of the magnetization $\delta\boldsymbol{m}_l$. Then, the values of the components of the dynamic susceptibility of each cell are calculated: $\chi_{i,k,l} = \delta m_{l,i}/|h_k|$, $(i, k)=(x, y, z)$. Summing up them over all cells, we obtain the values of the components of the integrated dynamic susceptibility. Later in the article we consider its imaginary part $\chi_{i,k}''$.

The calculation was carried out for the parameters of a two-layer film characteristic of an iron-garnet film $M_1 \approx 30$ G, $M_2 \approx 70$ G, $J \approx 1\ \text{cm}^{-1}$, $\alpha_i \approx 10^7$ erg/cm. The layer thicknesses are $d_1 \approx 0.5 \times 10^{-4}$ cm and $d_2 \approx 0.18 \times 10^{-4}$ cm. The anisotropy parameters are $K_{u,1}^* \approx 2 \times 10^4\ \text{erg/cm}^3$, $K_{u,2}^* \approx -7 \times 10^4\ \text{erg/cm}^3$, $K_1 \approx -2 \times 10^4\ \text{erg/cm}^3$.

3. Results and discussion

Up to the saturation field, the ground state of the film is inhomogeneous. At low fields in case the sample with a combined cubic and uniaxial magnetic anisotropy of layers on the outer boundaries of the layers, the magnetization deviates toward one of the trigonal axes from the normal for the first layer, and from the film plane for the second layer. For the sample with a uniaxial magnetic anisotropy of layers we assumed that, without a loss of generality, it is possible to consider that the magnetization rotates in the plane (x, y), so that only the angle ϕ depends on the coordinate x.

Let us consider the effect of changes in static and dynamic components of the magnetization on the behavior of the amplitude of the integrated dynamic susceptibility and frequency when the film is being magnetized by an external field. The field has been applied in one of three directions: along the [100], [011] or [010] axes. As these changes most influence the amplitude of the dynamic susceptibility of the lower FMR mode, later in this article we consider in more detail this mode. The amplitudes of the various components of the dynamic susceptibility vary considerably depending on the strength and direction of the external magnetic field.

Let us consider the case when the external field is applied along the [100] axis. For the lower FMR branch of the sample with a combined cubic and uniaxial magnetic anisotropy all components are significant except χ_{yx}''. Fig. 2 shows the dependences components of the integrated dynamic susceptibility of the lower FMR mode χ_{zz}'' (Fig. 2a) and χ_{yy}'' (Fig. 2b), as well as the frequencies of lower and upper FMR modes (Fig. 2c) on the external magnetic field.

Figs. 3 and 4 show the dependences of the susceptibility component $\chi_{zz,l}''$ of the lower and upper FMR modes on the coordinate x for different values of the external magnetic field.

At low fields, the lower FMR mode is localized in the first layer. It is distributed over a layer non-uniformly. The maximum of the distribution of the dynamic susceptibility is at the outer boundary of the first layer. With increasing of the field there is a shift of the localization of the lower FMR mode to the interlayer boundary. Then it is localized in the second layer. At the same time there is a change of localization of the upper FMR mode. It shifts from the second to the first layer.

The displacement of the modes corresponds to the field H_1 in Fig. 2. The component χ_{zz}'' throughout the range of variation of the field is greater than other components. It is highest at low fields, and then, with the increase of the field, its amplitude decreases. When the field strength approaches the value H_{st} at which the