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Nonlinear dynamics of magnetic oscillations and orientation transitions in three-layer anisotropic films

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In this paper, orientational transitions of magnetization vectors in a three-layer structure are considered, taking into account the exchange interaction of edge anisotropic magnetic layers due to varying the thickness of the non-magnetic buffer between them. Changing the material parameters of the structure entails reconfiguration of the components of the magnetization vectors. The reconfiguration data are interpreted from graphical time, frequency, and parametric dependencies using numerical solutions of the Landau-Lifshitz-Hilbert equations. The influence of changes in the material parameters of the structure on the behavior of orientation transitions of the magnetization vectors is investigated.

Keywords: multilayer structure, orientation transitions, exchange coupling, cubic anisotropy.

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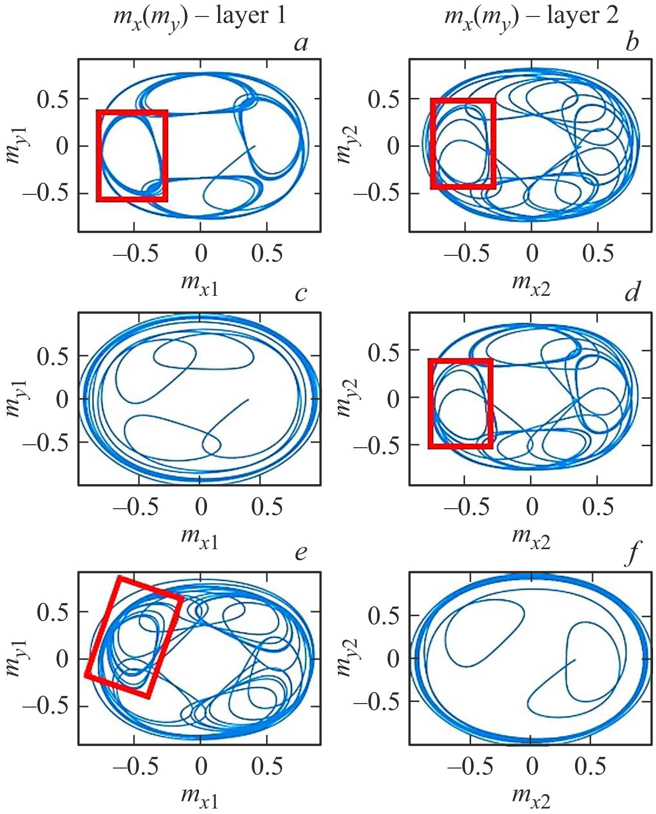
In the last decade the non-linear magnetic dynamics has been actively studied in connection with applications in spintronics when developing spin transistors and memory cells MRAM [1]. Use of multi-layer magnetic films is based on detection of certain patterns and effects, such as multiple change in the frequency of vibrations, generation of new vibrational modes, transfer of the spin rotary torque, which are based on quantum-mechanical nature and orientation transitions in multilayer structures [2–5]. These effects help to use these structures in modern electronics [1,2]. This paper studied magnetic orientation transitions arising when nonlinear magnetic vibrations are present in the magnetic layers of the structure. Previously papers [5,6] found the modes for precession of the equilibrium position of the magnetization vector, deployed circular precession, the mode of precession frequency division into three intervals. Besides, the ambiguous effect of the exchange interaction field was detected, being set by the coefficient of exchange coupling J between the adjacent magnetic layers. This ambiguity manifested itself in the presence of the alternating magnetic field amplitude interval, where chaotic vibrations of magnetization vector occurred [7]. This paper conducted the computational modeling of magnetization vector vibrations under the conditions of orientation transition in a three-layer structure magnetized along the normal line, with orientation of the magnetic anisotropy fields along axis [001]. To model the magnetic dynamics for two magnetic layers, a system was recorded from three non-linear ordinary differential equations based on the Landau-Lifshitz vector equation [5]. Accounting of the interaction between the two adjacent magnetic layers of the structure via the non-magnetic thin layer reduces the objective of the magnetic dynamics to the system of six differential equations, which in this paper were solved numerically bu Runge-Kutta method of 4−5 order:

$$\frac{\partial m_{x1}}{\partial t} = -\frac{\gamma}{1+\alpha_1^2}\cdot\Big[(m_{y1}+\alpha_1 m_{x1}m_{z1})\cdot H_{ez1} - (m_{z1}-\alpha_1 m_{y1}m_{x1})\cdot H_{ey1} - \alpha_1\cdot(m_{y1}^2+m_{z1}^2)\cdot H_{ex1}\Big], \quad (1)$$

$$\mathbf{H}_e = -\frac{1}{M_0}\frac{\partial U}{\partial \mathbf{m}},\ U = -M_0 h_x m_x - M_0 h_y m_y - M_0 H_{0z} m_z + 2\pi M_0^2 m_z^2 + 2J\mathbf{M}^2 + K(m_x^2+m_y^2+m_z^2), \quad (2)$$

where m_{i1} — single i-component $(i = x, y, z)$ of 1-layer, γ — gyromagnetic ratio for electron spin, $\alpha_1 = 0.15$ — coefficient of magnetic dissipation of the layer, M_0 — magnetization of layer saturation, $h_{x,y}$ — components of alternating magnetic field, H_{0z} — permanent magnetic field along Oz, J — coefficient of exchange interaction, K — anisotropy constant.

Cyclic shifting of indices x, y, z in (1) makes it possible to obtain differential equations for one of the magnetic layers, and replacement of index 1 for 2 makes it possible to find this system of equations for the second magnetic layer. The expression for the free density of energy of the magnetic layer makes it possible to find the equations for the effective magnetic fields using energy differentiation along the magnetization components (2). Since the layer magnetization vector is a single magnetic domain provided that the film size is much larger than its width, in the calculations we used the approximation of the homogeneous magnetization model in the structure layers. The calculations assumed that the dissipation constants of magnetic layers were identical $\alpha_1 = \alpha_2$, the anisotropy



Portraits of vibrations of single components in the magnetization vector for two magnetic layers of three-layer structure with the growth of the coefficient of exchange coupling J, erg/cm^3: 0 (a, b), 57 (c, d), 155 (e, f). The left column of the figures (a, c, e) refers to the first layer, and the second column of the figures (b, d, f) refers to the second layer. The red rectangle shows the areas of vibration condensation or potential wells, between which the switching takes place.

constant $K = 1350\,\text{erg/cm}^3$ is also identical for both layers of the film, and the magnetization value of the adjacent layers differs insignificantly: $M_{01} = 23.1\,\text{G}$, $M_{02} = 22.7\,\text{G}$. Magnetization values and magnetic anisotropy constants were chosen close to the similar constants for crystal $Y_3Fe_5Al_1O_{12}$ [7]. The exchange field of magnetic layers interaction was taken as proportionate to magnetization [5]. The external fields that were considered included the circle-polarized alternating magnetic field with amplitude 55 Oe and frequency 500 MHz, oriented in the plane of magnetic layers, and permanent magnetic field, with the value of 265 Oe, was directed along the normal line to the plane of the structure.

Analysis of numerical solutions to the system of equations demonstrated that a transition mode occurs in the magnetic layers of the structure, within which a high-amplitude vibration mode was established in one of the layers with transition from one potential barrier to the other, and in the other layer the classic precession of the magnetization vector equilibrium position is created (see Figure). As the constant of exchange interaction J or exchange field increases, a critical transition occurs, when the magnetic dynamics in the layer changes to the opposite one (Figure a–d). Besides, the classic precession of the magnetization vector was established in the layer with the transitions between the barriers, and in the adjacent one — transitions took place from a barrier to a barrier (Figure c, d). One may say that the exposure to the exchange field causes morphological changes in the energy surface of the potential energy of the structure magnetic layers. These changes are of periodical nature, which makes it possible to mention the alternating effect of the exchange field at the type of the portraits of magnetic vibrations. The overall series of the portraits of vibrations shows the following dynamics: at the values of the exchange field from 0 to 56 erg/cm^3 the images show the magnetic vibrations in the field of the energy minima provided for by the field of cubic anisotropy (Figure a, b). As the exchange energy increases further from 57 erg/cm^3, a dramatic transition is observed — localization of condensations in the first layer disappears, and for the second layer — localization of condensations is rather high, and is observed up to the value of 150 erg/cm^3 (Figure c, d). Further increasing the exchange value from 150 erg/cm^3, another dramatic transition is observed — in the first layer we can see the areas of magnetic vibrations near the local minima of energy (Figure e), while in the second layer the magnetization vector describes the high-amplitude vibrations up to the values of the coefficient of exchange coupling 170 erg/cm^3.

Therefore, this paper studied the nonlinear modes of magnetic vibrations and precession of magnetization vectors in the adjacent magnetic layers of the three-layer structure with orientation towards the axis of magnetic anisotropy along the crystallographic axis [001], directed along the normal line of the structure layers. As the exchange interaction increases between the magnetic layers of the structure, the bifurcation behavior of magnetization vector precession was found, which is characterized by the changes in the nature of condensations and rarefactions of the magnetization vector end movement trajectories on the portraits of magnetic vibrations. The obtained portraits of vibrations show that the positions of condensations of vibrations or potential wells move as the constants of exchange coupling change, and at certain constant values they are absent. The calculations show that in bifurcation transitions between different modes of layer magnetization vector precession there is a strong frequency shift of the low-frequency component in the precession frequency. These effects may be used in various electronic devices, for example in frequency conversion devices.

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Conflict of interest

The authors declare that they have no conflict of interest.

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