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Micromagnetic study of magnetization reversal in exchange spring systems with mutually orthogonal anisotropies

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ABSTRACT

Magnetization reversal in trilayer exchange spring systems with mutually orthogonal anisotropies was investigated. The micromagnetic calculation showed that a negative nucleation field could be formed when the soft layer was sufficiently thick. The change rate of the magnetization direction in the soft layer was determined to be faster than that in the hard layer. The rate could be engineered by varying the ratios of the anisotropy constant and exchange energy constant. Structures with different hard layer thicknesses showed similar effects on the angular change rate ratio.

1. Introduction

Exchange spring systems, which are composed of alternating soft and hard magnetic layers, have been extensively studied [1–3]. These structures are expected to combine the high coercivity of the hard phase and the high saturation magnetization of the soft phase. This combination is advantageous in consistently achieving high-energy products with high remanence, making exchange-coupled magnetic layers excellent candidates [4,5]. The switching field of a recording layer can be effectively reduced by the exchange field from a neighboring soft layer, and such reduction enhances the applicability of exchange spring systems in ultrahigh density magnetic recording media [6–10]. Understanding the surface and interface magnetism of exchange spring systems is crucial in fine-tuning their properties. Researchers have adopted several methods, such as spin wave excitations [11–13], heat assistance [6,7,14], electric field control [15], and insertion of non-magnetic spacers [16], to explore exchange spring systems. In addition, many theoretical studies have explored magnetization reversal in soft/hard multilayered structures [17,18].

In previous studies, the magneto crystalline easy axes of the soft and hard layers of exchange spring systems are in the same direction (i.e., either parallel or perpendicular to the film plane). Only a few studies have investigated exchange spring systems with mutually orthogonal anisotropies, in which the easy axes of the soft and hard layers are perpendicular with each other [10,19,20]. In these structures, the switching field of the soft (hard) layer can be tailored by adding a well-coupled hard (soft) layer. Whereas most of these works are focused on bilayer structures, the present study considers a hard/soft/hard trilayer exchange spring system, in which the crystalline easy axis of the soft layer is parallel to the film plane and the easy axes of the hard layers are perpendicular to the film plane. $Pt_{84}Co_{16}$ and TbFeCo are used as examples of soft and hard layer materials, respectively. The negative nucleation field, angular distributions of magnetization, and magnetic hysteresis loops are also comprehensively discussed.

2. Calculation model

A trilayer system shown in Fig. 1 is analyzed. In this system, a soft film is sandwiched between two hard films with the same thickness. The easy axes of both hard layers are perpendicular to the films, whereas the easy axis of the soft layer is parallel to the film plane. We consider a downward initial magnetization of the hard layers and an initial magnetization of the soft layer along the x axis, as shown in Fig. 1. The angle θ is defined between the negative direction of the z axis and the magnetization direction. A positive external field H is considered. All layers are infinite in the lateral dimensions, and the magnetization distributions are uniform in the x and y directions. In this case, the system can be simulated using a

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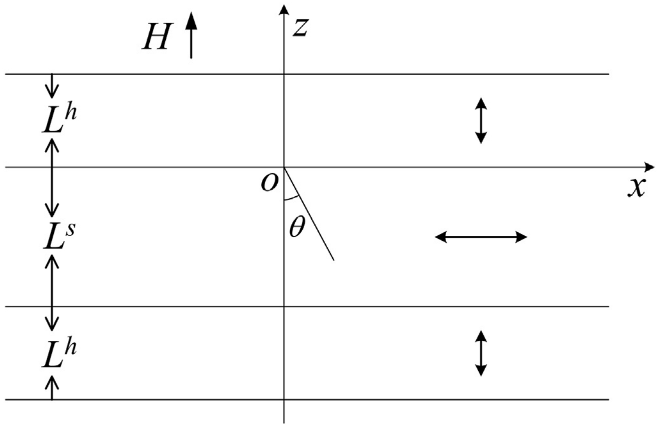

Fig. 1. Basic scheme for the one-dimensional continuum micromagnetic model.

one-dimensional model.

Given the symmetry of this system, the integer region limited within $-L^s/2 \le z \le L^h$ is enough. A reduced interlayer exchange coupling is supposed. Therefore, the total magnetic energy per unit area in this system can be expressed as

$$\gamma = \int_{-\frac{L^s}{2}}^{0}\left[A^s\left(\frac{d\theta}{dz}\right)^2 + K^s\cos^2\theta + HM_s^s\cos\theta\right]dz + \int_{0}^{L^h}\left[A^h\left(\frac{d\theta}{dz}\right)^2 + K^h\sin^2\theta + HM_s^h\cos\theta\right]dz - \frac{J_s}{a^2}\left(\vec{m}_s\cdot\vec{m}_h - 1\right), \tag{1}$$

where $K^s = \left|K_\mu^s + 2\pi(M_s^s)^2\right|$, $K^h = \left|K_\mu^h - 2\pi(M_s^h)^2\right|$, and the superscripts h and s refer to the soft and hard layers, respectively. A and K are the exchange energy constant and the absolute value of the anisotropy constant, respectively. H is the applied field, and $M_s^q(q=s,h)$ is the spontaneous magnetization. The anisotropy constant has two parts, namely, the uniaxial anisotropy part $K_\mu^q(q=s,h)$ and the demagnetization part $2\pi(M_s^q)^2(q=s,h)$. J_s is the interlayer exchange constant, and a is the inter-atomic distance on a specific atomic plane. $\vec{m}_s$ and $\vec{m}_h$ are the magnetization unit vectors of the soft and hard layers, respectively.

The following boundary conditions are considered [21]:

$$\left.\frac{d\theta}{dz}\right|_{z=L^h} = \left.\frac{d\theta}{dz}\right|_{z=-L^s/2} = 0, \tag{2a}$$

$$A^s\left.\frac{d\theta}{dz}\right|_{z=0^-} = A^h\left.\frac{d\theta}{dz}\right|_{z=0^+} = \frac{J_s}{2a^2}\sin(\theta_{0^+} - \theta_{0^-}). \tag{2b}$$

where θ_{0^+} and θ_{0^-} denote the deviate angles at the hard/soft interface of the hard layer side ($z>0$) and the soft layer side ($z<0$), respectively.

The minimization of Equation (1) leads to the following Euler–Lagrange equations for the soft and hard layers:

$$2A^s\frac{d}{dz}\left(\frac{d\theta}{dz}\right) = -2K^s\sin\theta\cos\theta - HM_s^s\sin\theta, \tag{3a}$$

$$2A^h\frac{d}{dz}\left(\frac{d\theta}{dz}\right) = 2K^h\sin\theta\cos\theta - HM_s^h\sin\theta. \tag{3b}$$

Upon integrating and considering the boundary condition (2b), we obtain the following equations:

$$A^s\left(\frac{d\theta}{dz}\right)^2 = K^s\left(\sin^2\theta^s - \sin^2\theta\right) + HM_s^s(\cos\theta - \cos\theta^s), \tag{4a}$$

$$A^h\left(\frac{d\theta}{dz}\right)^2 = K^h\left(\sin^2\theta - \sin^2\theta^h\right) + HM_s^h\left(\cos\theta - \cos\theta^h\right). \tag{4b}$$

where θ^s and θ^h are the angles θ in the middle of the soft layer ($z = -L^s/2$) and on the free surface of the hard layer ($z = L^h$), respectively.

Integrating the preceding equations yields

$$\pi\left(\frac{L^s/2 + z}{\Delta^s}\right) = \int_{\theta}^{\theta^s}\left(\frac{1}{(\sin^2\theta^s - \sin^2\theta) + 2h^s(\cos\theta - \cos\theta^s)}\right)^{1/2} d\theta, \tag{5a}$$

$$\pi\left(\frac{L^h - z}{\Delta^h}\right) = \int_{\theta^h}^{\theta}\left(\frac{1}{\left(\sin^2\theta - \sin^2\theta^h\right) + 2h^h\left(\cos\theta - \cos\theta^h\right)}\right)^{1/2} d\theta, \tag{5b}$$

where $\Delta^s = \pi\sqrt{A^s/K^s}$, $\Delta^h = \pi\sqrt{A^h/K^h}$, $h^s = HM_s^s/2K^s$, and $h^h = HM_s^h/2K^h$.

Equations (3a) and (3b) are related by Equation (2b), which can be rewritten as

$$\left(\frac{J^i}{2a^2}\right)^2\sin^2(\theta_{0+} - \theta_{0-}) = A^sK^s\left[\left(\sin^2\theta^s - \sin^2\theta_{0-}\right) + 2h^s(\cos\theta_{0-} - \cos\theta^s)\right], \tag{6a}$$

$$\left(\frac{J^i}{2a^2}\right)^2\sin^2(\theta_{0+} - \theta_{0-}) = A^hK^h\left[\left(\sin^2\theta_{0+} - \sin^2\theta^h\right) + 2h^h\left(\cos\theta_{0+} - \cos\theta^h\right)\right]. \tag{6b}$$

The angle distributions of magnetization through the whole system can be calculated by numerically solving Equations (5) and (6).

At the nucleation state, the deviation of magnetization from the saturated state is extremely small (θ is very small). As L^h is thick enough, θ^h can be assumed as 0. Then equations (5) and (6) are then simplified, and an implicit solution of the nucleation field is obtained, that is,

$$\sqrt{\frac{A^hK^h(1-h^h)}{A^sK^s(1+h^s)}} = \tan\left(\frac{L^s}{2\Delta^s}\sqrt{1+h^s}\right)\left(1 + \frac{2a^2}{J^i}\sqrt{A^hK^h(1-h^h)}\right). \tag{7}$$