Journal of Magnetism and Magnetic Materials 381 (2015) 28–33

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Micromagnetic simulation of exchange coupled ferri-/ferromagnetic heterostructures

Harald Oezelt [a,*], Alexander Kovacs [a], Franz Reichel [a], Johann Fischbacher [a], Simon Bance [a], Markus Gusenbauer [d], Christian Schubert [b,c], Manfred Albrecht [b,c], Thomas Schrefl [a,d]

[a] Industrial Simulation, St. Pölten University of Applied Sciences, Matthias Corvinus-Straße 15, A-3100 St. Pölten, Austria
[b] Institute of Physics, Chemnitz University of Technology, Reichenhainer Straße 70, D-09126 Chemnitz, Germany
[c] Institute of Physics, University of Augsburg, Universitätsstraße 1, D-86159 Augsburg, Germany
[d] Center for Integrated Sensor Systems, Danube University Krems, Viktor Kaplan-Straße 2, A-2700 Wiener Neustadt, Austria

ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
5 December 2014
Accepted 16 December 2014
Available online 23 December 2014

Keywords:
Exchange-coupled composite media
Micromagnetic simulations
Ferrimagnet
FEM
Domain wall motion
Finite size effect
Pinning

ABSTRACT

Exchange coupled ferri-/ferromagnetic heterostructures are a possible material composition for future magnetic storage and sensor applications. In order to understand the driving mechanisms in the demagnetization process, we perform micromagnetic simulations by employing the Landau–Lifshitz–Gilbert equation. The magnetization reversal is dominated by pinning events within the amorphous ferrimagnetic layer and at the interface between the ferrimagnetic and the ferromagnetic layer. The shape of the computed magnetization reversal loop corresponds well with experimental data, if a spatial variation of the exchange coupling across the ferri-/ferromagnetic interface is assumed.

1. Introduction

Ferrimagnetic materials have been widely used as magneto-optical recording media [1,2] and provide great potential for future devices in sensor technology and magnetic recording. Interest in ferrimagnetic materials has been renewed by experiments revealing all-optical switching of the magnetization [3–5] and the building of heterostructures leading to giant exchange bias [6]. Further applications of heterostructures built on ferromagnetic and ferrimagnetic layers might be found in magnetic recording media with tailored switching behaviour. The big advantage of these materials is the ability to tailor their magnetic properties by their composition with respect to the desired working temperature [7]. In order to exploit these properties we not only need to gain a deeper understanding of such materials but also need to investigate the exchange coupling with ferromagnetic materials. Exchange coupled composites (ECC) of hard- and soft-magnetic phases have already been proposed for the next generation of magnetic recording media [8] and may very well benefit even more from tailored ferrimagnetic layers.

Ferrimagnetic thin films have been extensively studied by Giles and Mansuripur et al. [9–12] in terms of magneto-optical recording. In their work they investigated the magnetization reversal dynamics and domain wall motion by utilizing an adapted Gilbert equation on a two dimensional lattice of magnetic dipoles. We will later use this approach in a three dimensional model system of ferrimagnetic thin films (see Section 2.1).

Yamada and his collaborators [13] experimentally showed the approach of using an exchange coupled magnetic capping layer on a ferrimagnetic layer (TbFeCo) to lower the required external field for magneto-optical recording. In contrast to our simulations the used capping layer had in-plane magnetization.

In experiments with strongly exchange coupled TbFe/FeCo multilayers, Armstrong et al. [14] revealed that demagnetization occurs by nucleation of a domain which extends through the entire layer-stack. A single twin wall is formed which moves until the whole sample is reversed. Contrary to our investigated model the layers are coupled antiparallel and have an in-plane easy axis.

Antiferromagnetically exchange coupled ferri-/ferrimagnetic bilayers have been investigated by Mangin et al. [15]. In their work they identified the magnetic configuration at the interface as the determining mechanism for the exchange bias field.

* Corresponding author.
E-mail address: harald.oezelt@fhstp.ac.at (H. Oezelt).

http://dx.doi.org/10.1016/j.jmmm.2014.12.045

A general micromagnetic model for exchange coupled bilayer systems was described by Oti [16]. He simulated laminated cobalt-alloy films used in longitudinal recording. The effect of media dimensions and interface exchange on magnetization at remanent and coercive states for two layers separated by a nonmagnetic phase were investigated. Both layers are modelled as an array of uniaxial volume elements and show an isotropic three-dimensional distribution of magnetocrystalline anisotropy axes.

Schubert and collaborators [17] experimentally investigated the interface exchange coupling of ferri-/ferromagnetic heterostructures with out-of-plane anisotropy. Their results revealed that an interfacial domain wall greatly affects the demagnetization process.

In this paper we start by taking Mansuripur's approach [11] for ferrimagnetic films with strongly coupled sub-lattices and implement it in a three-dimensional micromagnetic finite element calculation. We extend the model by adding a collinearly exchange-coupled continuous ferromagnetic layer. The magnetization reversal of this bilayer system is compared with recently accomplished experimental results [17]. Finally the demagnetization process is studied by visualizing and comparing the movement of domain walls through a single ferrimagnetic layer and a ferri-/ferromagnetic bilayer system.

2. The model system

2.1. Micromagnetic model for ferrimagnetic thin films

While the finite element simulation of ferromagnets is a common task, ferrimagnets have been simulated on their own and in two dimensions for the application in magneto-optical recording [12,18]. Ferrimagnets have different sublattices with unequal opposing magnetic moments, hence the mathematical model has to be adapted. By following Mansuripur [11], assuming that the sublattices are strongly coupled antiparallel, the usual Gilbert equation can be written for each of sublattices $L^{(a)}$ and $L^{(b)}$ as

$$\dot{\mathbf{M}}^{(a)} = -\gamma^{(a)}\mathbf{M}^{(a)} \times (\mathbf{H}^{(a)} + h\mathbf{M}^{(b)}) + \alpha^{(a)}\mathbf{M}^{(a)} \times \dot{\mathbf{m}}^{(a)} \tag{1a}$$

$$\dot{\mathbf{M}}^{(b)} = -\gamma^{(b)}\mathbf{M}^{(b)} \times (\mathbf{H}^{(b)} + h\mathbf{M}^{(a)}) + \alpha^{(b)}\mathbf{M}^{(b)} \times \dot{\mathbf{m}}^{(b)} \tag{1b}$$

The sublattice $L^{(a)}$ is defined by its magnetization magnitude $M^{(a)}$ and its unit vector $\mathbf{m}^{(a)} = \mathbf{M}^{(a)}/M^{(a)}$, the gyromagnetic ratio $\gamma^{(a)}$ and the corresponding damping parameter $\alpha^{(a)}$. The field on the subnet $L^{(a)}$ is split into the effective local exchange field $h\mathbf{M}^{(b)}$ of subnet $L^{(b)}$ acting on subnet $L^{(a)}$ and the remaining effective fields $\mathbf{H}^{(a)}$. This notation applies to the sublattice $L^{(b)}$. h is the effective coupling constant between the sublattices. Because of reciprocity of the exchange energy, h is the same for each sublattice. Due to the strongly coupled sublattices, the magnetic moments $\mathbf{M}^{(a)}$ and $\mathbf{M}^{(b)}$ will always stay antiparallel. Therefore the effective net magnetization can be defined as $\mathbf{M} = M\mathbf{m}$ with $M = M^{(a)} - M^{(b)}$ and $\mathbf{m} = \mathbf{m}^{(a)} = -\mathbf{m}^{(b)}$ (see Fig. 1).

By summing up Eqs. (1a) and (1b) and substituting the unit vectors, we achieve

$$\left(\frac{M^{(a)}}{\gamma^{(a)}} - \frac{M^{(b)}}{\gamma^{(b)}}\right)\dot{\mathbf{m}} = -\mathbf{m} \times (M^{(a)}\mathbf{H}^{(a)} - M^{(b)}\mathbf{H}^{(b)}) + \left(\frac{\alpha^{(a)}M^{(a)}}{\gamma^{(a)}} + \frac{\alpha^{(b)}M^{(b)}}{\gamma^{(b)}}\right)\mathbf{m} \times \dot{\mathbf{m}} \tag{2}$$

By defining the effective values as

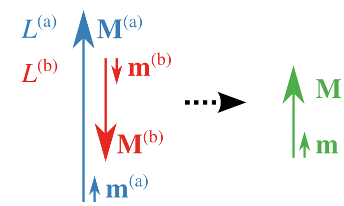

Fig. 1. In this model the magnetic moments $\mathbf{M}^{(a)}$ and $\mathbf{M}^{(b)}$ of the sublattices $L^{(a)}$ and $L^{(b)}$ of a ferrimagnet are assumed to be antiparallel at all times and therefore substituted by an effective net magnetization $\mathbf{M}$.

$$\gamma_{\text{eff}} = \frac{M^{(a)} - M^{(b)}}{\frac{M^{(a)}}{\gamma^{(a)}} - \frac{M^{(b)}}{\gamma^{(b)}}} \tag{3}$$

$$\alpha_{\text{eff}} = \frac{\frac{\alpha^{(a)}M^{(a)}}{\gamma^{(a)}} + \frac{\alpha^{(b)}M^{(b)}}{\gamma^{(b)}}}{\frac{M^{(a)}}{\gamma^{(a)}} - \frac{M^{(b)}}{\gamma^{(b)}}} \tag{4}$$

$$\mathbf{H}_{\text{eff}} = \frac{M^{(a)}\mathbf{H}^{(a)} - M^{(b)}\mathbf{H}^{(b)}}{M^{(a)} - M^{(b)}} \tag{5}$$

the Gilbert equation of a strongly coupled ferrimagnetic thin film is obtained:

$$\dot{\mathbf{m}} = -\gamma_{\text{eff}}\mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha_{\text{eff}}\mathbf{m} \times \dot{\mathbf{m}} \tag{6}$$

We particularize Eq. (5) by splitting the effective fields $\mathbf{H}^{(a)}$ and $\mathbf{H}^{(b)}$ into a sum of their components: the external field $\mathbf{H}_{\text{ext}}$, the demagnetizing field $\mathbf{H}_{\text{dmag}}$, the anisotropy field $\mathbf{H}_{\text{ani}}$ and the exchange field $\mathbf{H}_{\text{xhg}}$. The external field and the demagnetizing field are equal for both subnets:

$$\mathbf{H}^{(a)}_{\text{dmag}} = \mathbf{H}^{(b)}_{\text{dmag}} = \mathbf{H}_{\text{dmag}} \tag{7}$$

$$\mathbf{H}^{(a)}_{\text{ext}} = \mathbf{H}^{(b)}_{\text{ext}} = \mathbf{H}_{\text{ext}} \tag{8}$$

For the anisotropy field we assume a common anisotropic easy axis, defined by an unit vector $\mathbf{k}$, but different magnetic anisotropy constants $K^{(a)}_{\text{u}}$ and $K^{(b)}_{\text{u}}$:

$$\mathbf{H}^{(a)}_{\text{ani}} = \frac{2K^{(a)}_{\text{u}}}{M^{(a)}}(\mathbf{m}^{(a)}\cdot\mathbf{k})\mathbf{k} \tag{9a}$$

$$\mathbf{H}^{(b)}_{\text{ani}} = \frac{2K^{(b)}_{\text{u}}}{M^{(b)}}(\mathbf{m}^{(b)}\cdot\mathbf{k})\mathbf{k} \tag{9b}$$

The exchange fields have different exchange constants $A^{(a)}_{\text{x}}$ and $A^{(b)}_{\text{x}}$ and are proportional to the Laplacian of their respective magnetization:

$$\mathbf{H}^{(a)}_{\text{xhg}} = \frac{2A^{(a)}_{\text{x}}}{{M^{(a)}}^2}\nabla^2\mathbf{M}^{(a)} \tag{10a}$$

$$\mathbf{H}^{(b)}_{\text{xhg}} = \frac{2A^{(b)}_{\text{x}}}{{M^{(b)}}^2}\nabla^2\mathbf{M}^{(b)} \tag{10b}$$

We define an effective net anisotropy constant $K_{\text{u}} = K^{(a)}_{\text{u}} + K^{(b)}_{\text{u}}$ and an effective net exchange stiffness constant $A_{\text{x}} = A^{(a)}_{\text{x}} + A^{(b)}_{\text{x}}$ and rewrite Eq. (5) with $M = M^{(a)} - M^{(b)}$ as follows:

$$\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ext}} + \mathbf{H}_{\text{dmag}} + \underbrace{\frac{2K_{\text{u}}}{M}\left(\mathbf{m}\cdot\mathbf{k}\right)\mathbf{k}}_{\mathbf{H}_{\text{ani}}} + \underbrace{\frac{2A_{\text{x}}}{M}\nabla^2\mathbf{m}}_{\mathbf{H}_{\text{xhg}}} \tag{11}$$