Stokes/Anti Stokes Modes in Co/CoPt Magnetic Recording Media

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Abstract

Here in this paper frequency dependence of Exchange spring Co/CoPt to the external field is being calculated by suggesting a random exchange approach to the exchange bias problem. The film is modeled as a finite series of layers. Each layer has infinite array of dipoles of spin S arranged on a square lattice. The FM/AFM interface is suggested not to be completely perfect due to chemical intermixing and surface disorder at the interface. So, a magnetically disordered interface between F and AF layer is assumed to behave like spin glass system. So spin glass behavior is assumed to occur which incorporates the effect of interface roughness. This model will help us to estimate the strength of the interface exchange field. According to this model, the external magnetic field can influence on the reorientation of the CoPt/Co interface and bulk magnetization and thus the interface energy between the CoPt and Co layer varies with external field. The experimental evidence is recently being observed in anisotropic magneto resistance measurements, lending support to our proposal. The results of calculated spectra for scattering found in exchange-coupled CoPt/Co bilayers compared with the experimental data. Stokes/anti-Stokes frequencies difference and also Stokes/anti-Stokes peak intensity ratio and asymmetry in peak frequency between the Stokes and anti-Stokes spectra is described. There is a reasonable agreement between the theory presented and experimental data.

Key words : spin glass, magnetic media, perpendicular magnetic recording

I. Introduction

Exchange bias is commonly manifested as the hysteresis-loop shift observed when a FM is in contact with an AFM layer across their common interface[1]. Exchange bias has been studied in a variety of systems including nano particles, layered films and inhomogeneous materials. This effect is considered to be the basis of design and operation of spin valves, magnetic tunnel junctions, spin electronic devices and magnetic recording industry. A comprehensive understanding of exchange bias is a long-standing problem involving fundamental questions of surface and interface Magnetism [2-3]. There have been numerous studies about the magnetic behavior of FM/AFM bi layers [4-11]. One of the key issues that has emerged is the role of disorder and frustration. The results of the magnetization dynamics study could be explained with a model invoking the randomness of the coupling between AF and F layers which originates from the frustration of exchange interactions at the AF/F interface.

II. Model

Models of exchange bias have many properties in common with models of spin glasses and other random magnets[12-17]. Disorder may lead to randomness either in exchange interaction[4] or in anisotropy[17] which implies a strong connection to spin-glass-like behavior[4,5,12]. It is believed that there is enough experimental evidence to consider the interface between the AF/F layers as a disordered state behaving similar to a spin-glass system [12-23]. Here in this paper the excitations of the long wavelength in exchange-coupled hard/soft CoPt/Co bilayers using is discussed using magnon scattering mechanism due to the roughness occurs at the interface. Frequency dependence of Exchange spring Co/CoPt to the external field is being calculated by suggesting a random exchange approach to the exchange bias problem. Frequency varies as a function of magnetic field via BLS experiment. The film is modeled as a finite series of layers. Each layer has infinite array of dipoles of spin S arranged on a square lattice. The FM/AFM interface is suggested not to be
completely perfect due to chemical intermixing and surface disorder at the interface. So, a magnetically disordered interface between F and AF layer is assumed to behave like spin glass system. So spin glass behavior is assumed to occur which incorporates the effect of interface roughness. This model will help us to estimate the strength of the interface exchange field. According to this model, the external magnetic field can influence on the reorientation of the CoPt/Co interface and bulk magnetization and thus the interface energy between the CoPt and Co layer varies with external field. Interface disordered and magnetic roughness can provide a weak AF interface region. AF layer is assumed to contain two types of AF states: One part has a weak anisotropy and there is a competition among the different interactions between the moments. There is no single configuration of the spins which is uniquely favored by all interactions (frustrated). Another part has a large anisotropy with a collection of spins which remains in a frozen disordered state even at low-temperatures. The spin orientation ruled by the AF spins (frozen). A fraction of the frustrated interfacial spins do rotate almost in phase with the F spins. Spin glass system has partially random interactions. This partial random state will be introduced in our model as a reduced interfacial exchange energy (effective exchange-Jeff) which is the related to the frustrated and rotatable AF spins, SG interface, and some of F spins. The experimental evidence is recently being observed in anisotropic magneto resistance measurements, lending support to our proposal. The results of calculated spectra for scattering found in exchange-coupled CoPt/Co bilayers compared with the experimental data. Stokes/anti-Stokes frequencies difference and also Stokes/anti-Stokes peak intensity ratio and asymmetry in peak frequency between the Stokes and anti-Stokes spectra is described. There is a reasonable agreement between the theory presented and experimental data.

Spin wave excitations can be used as probes in order to determine magnetic properties at surfaces and buried interfaces[24]. Additionally, frequencies of long-wavelength spin waves can lie in the microwave region, and magneto static spin waves are of great importance for many high frequency signal processing technologies [25,26]. Most recently, spin wave excitations in confined geometries such as dots and wires [27] and spin wave propagation in non collinear magnetic structures [28-29] have become a focus of attention. Considering only long-wavelength region, S can be treated as a classical vector. Writing the Landau-Lifshitz equations of motion, we linearize these equations for small-amplitude oscillations. The equations can be solved in order to achieve frequency:

\[ H = - \sum_{-i,j \neq i} J_{ij} \vec{S}_i \cdot \vec{S}_j + H_{rand} - g\mu_B \sum_i H_m (\frac{S_i}{S}) \vec{S}_i \cdot \vec{z} \]

\[ - g\mu_B \sum_i (H_{Out} - 4\pi M_S) \frac{S_i}{S} \vec{S}_i \cdot \vec{y} - g\mu_B H \sum_i \vec{S}_i \cdot \vec{z} \]  

(1)

Since the interface is not completely perfect, it has a spin glass-like behavior. So, Site disorder and RKKY interactions can happen at the interface. These features can be replaced by a random set of bonds which satisfy a Gaussian distribution. According to this model there is no change in the randomness of spin sites and only the spin directions can vary. We write the Hamiltonian like this [30]:

\[ H_{rand} = -kT \sum_i \exp \left( \frac{1}{kT} \frac{\Delta}{2} \sum_{\alpha=1}^n S_i^\alpha S_f^\alpha \right) \]

(2)

Interface random effective field can be written as:

\[ \vec{H}_{eff}^{rand} = \frac{1}{N} \left( -\frac{1}{g\mu_B} \right) \frac{\partial H_{rand}}{\partial S_i} \]

(3)

\[ \vec{H}_{eff}^{rand} = \frac{1}{N} \left( \frac{\Delta^2}{kT} \frac{S_i S_j \vec{S}_j}{\mu_B} \right) \sum_{S_i} \exp \left[ \frac{1}{kT} \sum_{\alpha=1}^n \frac{\Delta}{2} \sum_{\alpha=1}^n S_i^\alpha S_f^\alpha \right] \]

(4)

And to the first order we have:

\[ \vec{H}_{eff}^{rand} = \frac{1}{N} \left( \frac{\Delta^2}{kT} \frac{S_i S_j \vec{S}_j}{\mu_B} \right) \Delta \vec{S} = \frac{\Delta^2}{kT} \langle S_i S_f \rangle \]

(5)
The effect of exchange can be eliminated by increasing randomness: when a layer is random it has a weaker exchange so the term of exchange in equation can be corrected like this: \( \vec{H}_{\text{eff}}^{\text{rand}} = \vec{H}_{\text{eff}}^{\text{ch}} - \vec{H}_{\text{eff}}^{\text{rand}} \) where

\[
\vec{H}_{\text{eff}}^{\text{rand}} = \frac{1}{N} \frac{\Delta_{\text{rand}}}{g \mu_B} (\vec{S} \cdot \vec{j})
\]

(6)

We calculate the parameter \( \Delta_{\text{rand}} \) in equation (5) for long wave-lengths. The correction to equation (1) cannot be noticeable for the x and y directions: in long wave-lengths \( \vec{S}_x \) and \( \vec{S}_y \) are small so the correction in equation (5) only affects on z direction:

\[
\begin{cases}
(S_{iz}, S_{iz} = 0), & S_{iz} = S_{iz} \\
(S_{iz}, S_{iz} = S_{iz})
\end{cases} \rightarrow \vec{J}_{\text{eff}x} = j_x, \vec{J}_{\text{eff}y} = j_y, \vec{J}_{\text{eff}z} = j_z - \Delta_{\text{eff}}
\]

(7)

Adding this to the effective field inequation (1) we have:

\[
\vec{H}_{\text{eff}} = \frac{1}{g \mu_B} (J_{co} \vec{S}_{co} + J_{eff} \vec{S}_{eff}) + H_{\text{ext}}^{\text{co}} (\vec{S}_{co}) + (H_{\text{ext}}^{\text{co}} - 4\pi M_{co}) \vec{S}_{co} \]

\[
+ \vec{H}_{\text{external}} (\vec{S}_{co} - \vec{S}_{co}) + 2\pi \kappa d_{co} \vec{M}_{co} \cdot \cos^2 \theta (\vec{S}_{co}) \vec{x} + 2\pi \kappa d_{co} \vec{S}_{co} \vec{y}
\]

\[
\vec{H}_{\text{eff}} = \frac{1}{g \mu_B} (J_{copt} \vec{S}_{copt} + J_{eff} \vec{S}_{eff}) + H_{\text{ext}}^{\text{copt}} (\vec{S}_{copt}) + (H_{\text{ext}}^{\text{copt}} - 4\pi M_{copt}) \vec{S}_{copt} \]

\[
+ \vec{H}_{\text{external}} (\vec{S}_{copt} - \vec{S}_{copt}) + 2\pi \kappa d_{copt} \vec{M}_{copt} \cdot \cos^2 \theta (\vec{S}_{copt}) \vec{x} + 2\pi \kappa d_{copt} \vec{S}_{copt} \vec{y}
\]

The applied field polarizes the SG interface layer. Polarization of the FM layer and some of frustrated AF interfacial spins can be added to these polarizations. These polarizations have a significant dependence on the applied field: At lower external fields, the effect of average random exchange is important. So, the FM/AFM interface has a spin-glass-like behavior. At higher external fields, magnetic field overcomes the average random exchange of the spin-glass-like interface and the interface moments would be aligned with the external field, and thus, the interface spin-glass behavior disappears. This means that Jeff which is affected by these polarizations, should be dependent to the external field so \( J_{eff} = f(H_{ext}) \). We use the derived effective field in the landau-lifshitz equations of motion as follows:

\[
\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{H}_{\text{eff}}
\]

(10)

For time dependent magnetization components in Co/CoPt system we take the magnetization components as:

\[
\begin{align*}
M_x &= M_{0, x} e^{-i\omega t} \\
M_y &= M_{0, y} e^{-i\omega t} \\
M_z &= M_{0, z}
\end{align*}
\]

(11)

Solving this equation with respect to the x and y components of magnetization, we will be able to obtain the frequency of magnons which is dependent to the magnetic properties of thin films. The obtained theoretical frequency is being compared with experimental ones.

III. Numerical Results

The material examined is a exchange spring bilayer which consists of 25nm of L10 CoPt with a <111> S out-of-plane and 16.7nm of Co with an HCP <0001> S out-of-plane Texture[31]. The parameters are: \( d_{co} = 16.7 \times 10^{-7} \text{cm}, d_{CoPt} = 25 \times 10^{-7} \text{cm} \). \( S_{Co} = 0.784 \mu_B, S_{CoPt} = 0.784 \mu_B \), \( S_{Co} = 1.31 \mu_B, S_{CoPt} = 1.31 \mu_B \). \( M_{Co} = 10053 \text{ Oe}, M_{CoPt} = 17593 \text{ Oe}, H_{\text{ext}}^{\text{co}} = 7143 \text{ Oe}, H_{\text{ext}}^{\text{copt}} = -6000 \text{ Oe} \).

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**Stokes/Anti Stokes Modes In Co/CoPt Magnetic Recording Media**

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\[ H_{\text{CoPt}}^{\text{CoPt}} = 106000 \text{ Oe} \]
\[ H_{\text{Co}}^{\text{Co}} = -38000 \text{ Oe} \]
\[ \theta = \frac{\pi}{4} \]
\[ J_{\text{CoPt}} = 92.48 \times 10^{-15} \text{ erg} \]
\[ J_{\text{Co}} = 45.6 \times 10^{-15} \text{ erg} \]
\[ k_x = 1.2 \times 10^4 \text{ Cm}^{-1} \]

The calculations have been made for a SG like interface. The magnitude of exchange parameter at the interface is unknown to the investigators due to the interface conditions but in some papers, the interfacial exchange coupling is assumed to be the average of the exchange coupling in the two bulk materials[9]. In our model \( j_x, j_y, j_z \) can be dependent to the external field \([8,9]\) and also \( \Delta_{\text{eff}} \):

During spin reversal, the SG interface layer and F spins reverse for the field \( H_{\text{ext}} = -2505 \text{ [Oe]} \) so, two set of parameters used. One set is before spin reversal and the other is after that. We take the dependence of \( \Delta \) and \( J_0 \) to be linear to external field:

\[
J_0 = \begin{cases} 
A_p H_{\text{external}} + B_p, & H_{\text{ext}} > -2505 \text{ [Oe]} \\
A_n H_{\text{external}} + B_n, & H_{\text{ext}} < -2505 \text{ [Oe]} 
\end{cases}
\]

The parameters \( A, B \) are chosen in order to have \( J_0(H_{\text{ext}}) \) average in the same order of \( 10^{-15} \text{ erg} \) which is in agreement with speculations in[11]. So we have:

\[
A_p = 4.64 \times 10^{-18} \quad B_p = 3.19 \times 10^{-14} \quad A_n = 1.97 \times 10^{-14} \quad B_n = -1.5 \times 10^{-14}
\]

For the term \( \Delta_{\text{eff}} \), it is noticeable that in the room temperature \( kT = 4.14 \times 10^{-14} \text{ erg} \). So \( \Delta_{\text{eff}} = \frac{\Delta^2}{kT} \langle S_x S_y \rangle \approx \frac{\Delta^2}{40 \times 10^{-14}} \) and \( \Delta \) should be in the order of \( 10^{-15} \text{ erg} \) for this model. So \( \Delta \) and \( J_0 \) would be comparable:

\[
\Delta = \begin{cases} 
C_p H_{\text{ext}} + D_p, & H_{\text{ext}} > -2505 \text{ [Oe]} \\
C_n H_{\text{ext}} + D_n, & H_{\text{ext}} < -2505 \text{ [Oe]} 
\end{cases}
\]

And we have:

\[
C_p = -0.82 \times 10^{-18} \quad D_p = 1.2 \times 10^{-14} \quad C_n = -0.62 \times 10^{-18} \quad D_n = -0.77 \times 10^{-14}
\]

Experimentally, the intensities of the peaks on the Stokes and anti-Stokes sides of the spectrum are nonequivalent [32]. Relative intensities for the magnon lines contain important information about magnon properties [33-43]. There are several physical effects which cause Stokes-anti-Stokes intensity ratio different from one. The main effect is related to the nonreciprocal propagation behavior of surface magnons[34]. For the magnetic field \( H \) into the page, the surface wave vector labeled \( +k \), can only be supported for a top surface magnon. The bottom surface can support only \( -k \). The propagation directions reverse for a reversal of the magnetic field. The amplitude of the surface magnon associated with one surface decays exponentially as one moves into the film with a decay length on the order of the in-plane propagation wavelength [35]. For the scattering geometry and the allowed surface magnon propagation directions discussed above, the scattering can only result in the creation of a surface magnon related to the top surface or the destruction of a magnon related to the bottom surface. The S/AS intensity ratio for the above situation will scale with the relative intensity of the top and bottom surface magnons at the top surface [35]. To a good approximation, this ratio is given by:

\[
S/AS = \exp(2k_Md)
\]

Where \( d \) is the film thickness and \( k_M \) is the in-plane propagation wave number. If the field is reversed, the above expression then apply to the anti-Stokes/Stokes ratio (AS/S). Qualitative support for this model has come from the observed inversion of the S/AS ratio for a reversal in the direction of the magnetic field[36, 37], or for the in-plane component of the incident light[38]. This inversion has become the main test for surface magnons. The Stokes to anti-Stokes peak ratio for the model and experiment are compared in Figure 1. for the film thickness, \( d_{\text{Co}, \text{CoPt}} = 41.7 \times 10^{-2} \text{ Cm} \) and \( k_M = 1 \times 10^4 \text{ Cm}^{-1} \). The calculations were found to be in agreement with experimental results. Damon–Eschbach surface modes are localized at one or the other surface of the Co film, depending on the direction of propagation and this is reflected by a frequency difference. The creation of a magnon results in a decrease in the frequency of the scattered light (Stokes peak) and magnon destruction yields an increase in the frequency of the scattered light (anti-Stokes peak). The experimental frequency difference between the Stokes and anti-Stokes peaks is shown in Figure 2 [7]. The line is calculated from our model. There
is a reasonable agreement between the experiment and the model. The dependence of frequency to the layer thickness is shown in Figure 2. The results are in agreement with [6, 32]. The thickness dependence of frequencies is plotted in figure 3. It is shown that the frequency decreases as thickness increases. It might be due to the omission of some volume modes of frequency when thickness decreases.

IV. Conclusion

On the basis of the experimental results, an approach to the problem of exchange bias is suggested. It relies on interacting magnetic defects at the interface. The roughness at the interface gives rise to a large fluctuating field because the FM magnetization interacts alternatively with one or the other AFM sublattice via atomic exchange coupling. The frequency of excitations of thin FM layer depends on the value of the interface exchange coupling field and degree of interface roughness. In conclusion, a model has been developed which can calculate light scattering intensities from exchange-spring structures, Stokes/anti-Stokes frequency difference and also Stokes/anti-Stokes peak intensity ratio. The calculations were found to be in agreement with experimental results. The model is an approach to the microscopic understanding of exchange bias and has important implications for future experimental and theoretical work.

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Stokes/Anti Stokes Modes In Co/Cu Magnetic Recording Media


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Figure Caption

Figure 1. Inversion of the S/AS ratio for a reversal in the direction of the magnetic field. For the magnetic field H into the page, the surface wave vector labeled +k and the bottom Surface can support only –k. The propagation directions reverse for a reversal of the magnetic field

Figure 2. Damon–Eschbach surface modes are localized at one or the other surface of the Co film, depending on the direction of propagation and this is reflected by a frequency difference.
Figure 3. Frequency to the layer thickness which is in agreement with [6, 32]