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Pulsed inductive microwave magnetometer response calculated for IrMn/FeNi bilayers

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Abstract. Micromagnetic simulations of a pulsed inductive microwave magnetometer (PIMM) experiment are performed using a well established model for exchange bias. The model (Interacting Grain Model) consists of ferromagnetic grains and antiferromagnetic grains with randomly distributed easy axes. A perfectly compensated interface between the ferromagnet and the antiferromagnet is assumed which leads to spin flop coupling. The antiferromagnetic layer is modelled as two totally antiparallel sublattices with a small intergrain exchange between each antiferromagnetic sublattice. Simulations of an experimental PIMM setup provide a shift of the minimum of the resonance frequency which is also observered experimentally.

PACS. 75.70.Cn Magnetic properties of interfaces (multilayers, superlattices, heterostructures) – 75.40.Mg Numerical simulation studies – 75.40.Gb Dynamic properties (dynamic susceptibility, spin waves, spin diffusion, dynamic scaling, etc.)

1 Introduction

Although discovered almost fifty years ago by Meiklejohn and Bean [1], exchange bias related phenomena are still of interest due to their vast exploitation in magnetic sensoring. Combining an antiferromagnetic layer with a ferromagnetic layer and cooling this two layers from above the Néel temperature of the antiferromagnet in an external field strongly affects the magnetic behavior. The most well-known phenomenon of such bilayers is a shift of the hysteresis loop along the field axis. This shift can be characterized by the introduction of an exchange bias field which can be calculated via

$$H_{eb} = \frac{H^+ + H^-}{2}. \tag{1}$$

H^+ denotes the intersection of the descending branch of the hysteresis loop with the field axis whereas H^- is the field value of the ascending branch of the loop on the field axis.

Exchange biased bilayers often exhibit a decrease of the exchange bias field with an increasing number of hysteresis loop measurements. After a few hysteresis cycles this ongoing decrease vanishes and the system exhibits a constant shift of the loop. This effect is called training effect and was investigated experimentally for NiFe/IrMn in [2]. Theoretically the training effect can be explained by the change of the antiferromagnetic domain structure after subsequent hysteresis loops as shown in the microscopic domain state model by Nowak and co-workers [3] or the mesoscopic interacting grain model by Suess and co-workers [4].

To investigate the dynamic response of exchange biased bilayers, more sophisticated methods are necessary. Pulsed inductive microwave magnetometry [6] (PIMM) is used to measure the high frequency response of antiferromagnetic/ferromagnetic bilayers by McCord et al. [7]. Thereby a short magnetic field pulse excites ferromagnetic resonance. This pulse is orientated normally to the external field H. The response of the ferromagnet is a precessional change of the magnetization. This response depends on the external dc field and on the internal field caused for example by an induced anisotropy [8]. Utilizing inductive sensors, this change can be quantified. For pure NiFe layers this response frequency ranges from several hundred MHz (no external dc field) to several GHz (strong external dc field) for thin Permalloy layers [6]. Considering thin magnetic layers, Kittel's formula [10] can be used to quantify the internal contributions:

$$f_{res} = \frac{\gamma\mu_0}{2\pi}\sqrt{M_s H_{\mathit{eff}}} \tag{2}$$

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γ denotes the gyromagnetic ratio ($\gamma = 1.8\ \mathrm{T^{-1}\,s^{-1}}$), μ_0 is the permeability of vacuum ($4\pi \times 10^{-7}$ Vs/Am) and M_s denotes the saturation magnetization of NiFe (M_s = 800 kA/m). The constituents of the effective field H_{eff} are H_K, which represents the uniaxial anisotropy of the NiFe layer, H_{rot}, which acts as an additional anisotropy in the same direction as the bias field, H_{eb}, which represents the shift of the hysteresis loop, and the external field H. The NiFe layer may exhibit a uniaxial anisotropy caused by a small external field applied during the deposition process [8]. The concept of a rotational anisotropy was introduced in order to explain the dependence of the hysteresis properties of exchange biased bilayers on the direction of the applied field. The rotational anisotropy is caused by irreversible switching processes in the antiferromagnet [9]. Assuming a constant H_K and H_{rot} during a hysteresis loop and a negative exchange bias field which is on the same axis as the bias field, equation (2) can be written as

$$f_{res}^2 = k(|x| + x_0) + d, \tag{3}$$

where $k = ((\gamma^2\mu_0^2)/(2\pi)^2)M_s$ and $d = ((\gamma^2\mu_0^2)/(2\pi)^2) \times (M_s(H_K + H_{rot}))$. x_0 denotes the dynamic exchange bias field [7], and x is the external field H. Thus, the minimum of f_{res}^2 represents the dynamic exchange bias field. A determination of the resonance frequency of an exchange biased system is therefore an alternative way to characterize the shift of the hysteresis loop. In our model we do not assume a uniaxial anisotropy in the NiFe layer. A contribution to the rotational anisotropy arises from the interaction of the magnetization of the ferromagnet with the domain configuration in the antiferromagnet.

The Interacting Grain Model

Suess et al. [4] introduced a micromagnetic model to describe exchange biased bilayers. Each layer is divided into 50×50 grains in each direction. Each quadratic grain has a side length of 10 nm and an adjustable height. The antiferromagnet is modelled with two equal sublattices. A weak intergrain exchange interaction between the grains of every sublattice is assumed. Furthermore the antiferromagnet is polycrystalline, which means the uniaxial easy axes are chosen randomly in space.

The ferromagnetic and the antiferromagnetic layer are 90° or spin-flop coupled at the interface as suggested by Koon [11]. Each antiferromagnetic interfacial spin of sublattice A has an opposing counterpart of the sublattice B. Thus, the interface is fully compensated. Furthermore, the system is free of any imperfections. Contrary to Koon's model, the Interacting Grain Model allows changes of the antiferromagnetic magnetization in three dimensions. The randomly distributed easy axes of the antiferromagnet induce domain processes in the antiferromagnet which in turn lead to exchange bias. Exchange bias can be explained by the domain wall energies of the antiferromagnet stored in domain walls vertical to the antiferromagnetic/ferromagnetic interface.

Table 1. Model parameters.

Quantity	Value	Unit
FM thickness	20	nm
FM uniaxial anisotropy	0	
AFM thickness	2 and 4	nm
AFM anisotropy constant	1×10^5	J/m^3
FM exchange constant	5×10^{-12}	
J/m AFM exchange constant	0.5×10^{-13}	
J/m FM-AFM exchange interaction	1×10^{-12}	
J/m damping constant α	0.01	

The field cooling process is simulated with a Metropolis Monte Carlo algorithm. Starting with an initial temperature of T_i = 800 K, the system is cooled towards 0 K in 25 K steps. During this part of the simulation the ferromagnet is fixed in y-direction whereas the antiferromagnet is allowed to rearrange. Subsequently the simulation of the hysteresis loop is performed by integrating the Landau-Lifshitz-Gilbert equation. The parameters used in this simulation are listed in Table 1.

A comprehensive description of the Interacting Grain Model including the numerical treatment of the Landau-Lifshitz-Gilbert equation can be found in [4]. The Interacting Grain Model shows the experimentally found dependence of both the exchange bias field and the coercivity on the thickness of the antiferromagnetic layer [4] and shows the training effect [5].

To simulate a PIMM experiment, the magnetic configuration at dedicated points of the hysteresis loop simulation is used to apply a 0.4 mT pulse perpendicular to the bias field. The rise time of this pulse is 200 ps. A subsequent integration of the Landau-Lifshitz-Gilbert equation delivers the dynamic response of the sample. A Fourier transformation is used to extract the resonance frequency.

Simulation results

The shift of the hysteresis loop depending on the antiferromagnetic thickness is investigated with both, the conventional methods using a simulation of the hysteresis loop and utilizing equation (1) and the PIMM method. Figure 1 shows PIMM simulation results for an antiferromagnetic/ferromagnetic bilayer with the thicknesses t_{AF} = 2 nm and t_{AF} = 4 nm. The bilayer with the thicker antiferromagnetic film shows a larger exchange bias field, H_{eb}, and a larger coercivity. With increasing thickness the minimum of the resonance frequency shifts towards the exchange bias direction. Following the numbered arrows in Figure 1, the frequencies on path 1 are larger than the frequencies obtained during return path 4. This is a direct consequence of the change in the antiferromagnetic domain structure. The simulation was started directly after the field cooling process. After reversing the ferromagnet from positive saturation to negative saturation, the antiferromagnet breaks up into small domains.

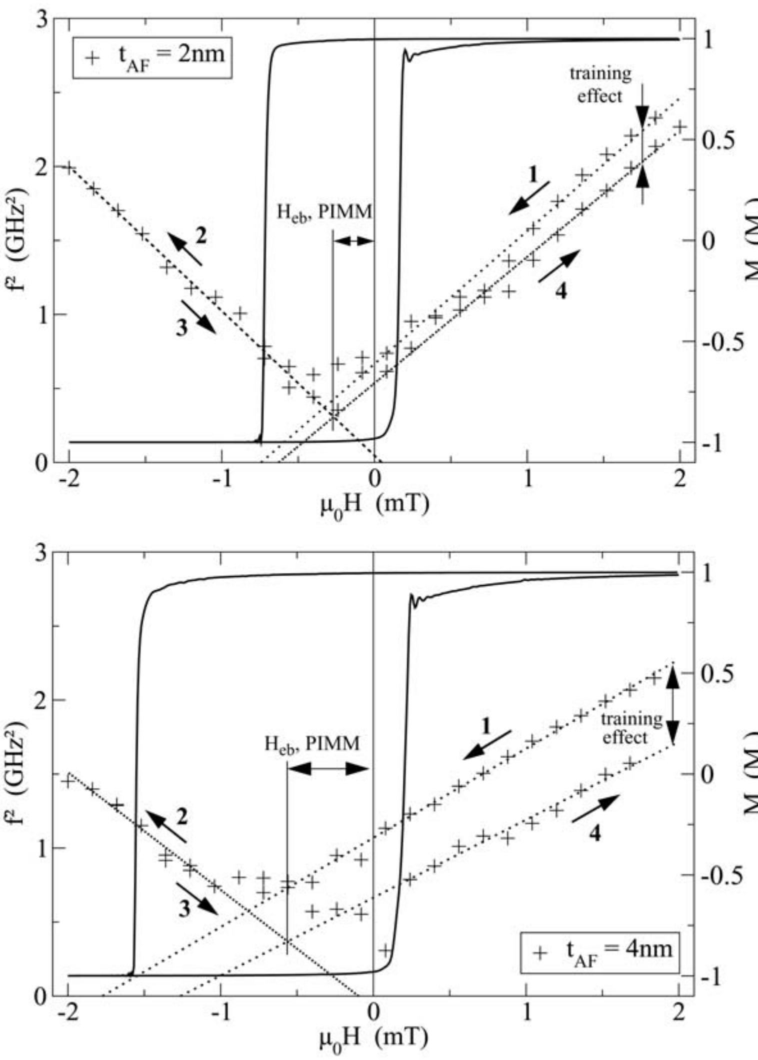

Fig. 1. PIMM simulation for antiferromagnetic thicknesses $t_{AF} = 2$ nm and $t_{AF} = 4$ nm, respectively. The dashed lines are linear regression fits of the simulated resonance frequencies outside the hysteretic regime ($R_{typ} = 0.98$). With increasing t_{AF} an increase of H_c and H_{eb} occur. Furthermore, the hysteresis loop simulation after field cooling is shown. The two different frequency paths on the positive field range (1 and 4) reflects the implications of the training effect. Subsequent hysteresis loop simulations will differ from the former in a decreased exchange bias field. This is due to changes in the antiferromagnet which occur during the reversal of the ferromagnet. This changes affect the effective field and thus the resonance frequency.

The initially large domains which are established during field cooling cannot be fully recovered on the final branch of the hysteresis cycle [4]. The antiferromagnetic domain structure is different on path 1 and on path 4. As a consequence the ferromagnet sees a different coupling field which results in a different ferromagnetic resonance frequency. After the first hysteresis cycle the antiferromagnetic domain structure is different from the domain structure established during field cooling. The difference in the antiferromagnetic domain structure after field cooling and after the first hysteresis cycle leads to a change in the exchange bias field and the coercive field. Both, H_{eb} and H_c decrease with the number of hysteresis cycles. In the Interacting Grain Model, the largest decrease occurs between the first and the second hysteresis cycle and both fields remain nearly constant for subsequent cycles [4,5]. The antiferromagnetic domain structure has reached a dynamic equilibrium: At a certain point of the hysteresis loop the antiferromagnetic domain configuration is always the same regardless of the number of hysteresis cycles. The PIMM results for the 2^{nd} hysteresis cycle, given in Figure 2, show negligible difference between path 1 and path 4. Now, at a given external field the antiferromagnetic domain structure is the same in the first and fourth branch of the loop, the ferromagnet feels the same coupling field. Consequently, the resonance frequency is the same for both branches at a given field.

To determine the exchange bias field with PIMM, the intersection of the frequency path 3 and path 4 are used. Determining the exchange bias field with path 3 and 4

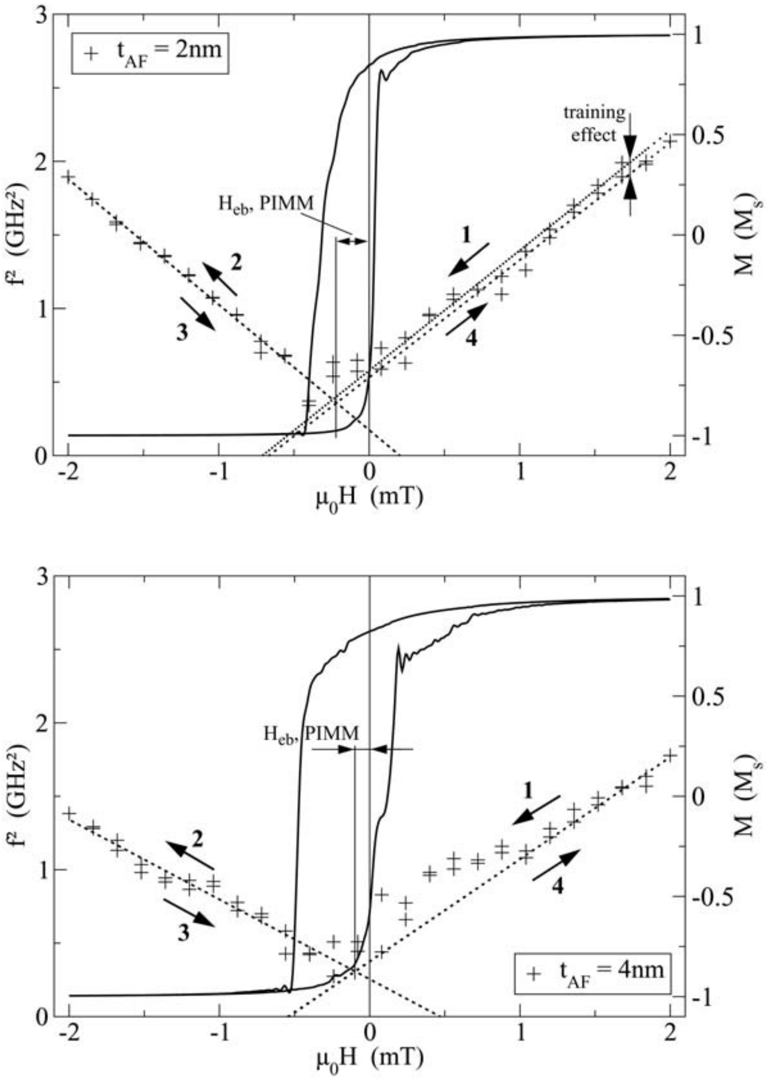

Fig. 2. Subsequent PIMM simulation (second hysteresis loop after field cooling). Both, the exchange bias field for 2 nm and for 4 nm AF layer respectively has been decreased (training effect). In the case of $t_{AF} = 4$ nm the difference between path 1 and 4 has been almost vanished, whereas in the case of $t_{AF} = 2$ nm there is still a small difference between path 1 and 4.

Table 2. Comparison between dynamically gathered H_{eb} (PIMM) and conventionally determined H_{eb} (Eq. (1)), first hysteresis loop.

loop 1	$\mu_0 H_{eb}$ PIMM	$\mu_0 H_{eb}$ conv.
$t_{AF} = 2$ nm	0.27 mT	0.277 mT
$t_{AF} = 4$ nm	0.57 mT	0.674 mT

Table 3. Comparison between dynamically gathered H_{eb} (PIMM) and conventionally determined H_{eb}, second hysteresis loop.

loop 2	$\mu_0 H_{eb}$ PIMM	$\mu_0 H_{eb}$ conv.
$t_{AF} = 2$nm	0.21 mT	0.14 mT
$t_{AF} = 4$nm	0.1 mT	0.17 mT

instead of path 1 and 2 takes into account the change in the antiferromagnetic domain structure which occurs after the first hysteresis loop.

The so derived exchange bias field is comparable to H_{eb} calculated from equation (1). A listing of the dynamically gathered values and the values for H_{eb} using the conventional values is given in Table 2 and Table 3, respectively. Both methods yield commensurable values. The exchange bias field was found to scale with the coercive field. This can be understood within the Interacting Grain Model. Within this model both exchange bias and coercivity are a result of the coupling of the ferromagnet to a specific antiferromagnetic domain state. A similar scaling of the exchange bias field with the coercive field is found experimentally in NiFe/IrMn bilayers for IrMn thicknesses below 4 nm [2].

Summary

It has been shown that few assumptions like the randomness of the antiferromagnetic easy axes, weak exchange coupling between the grains of the antiferromagnet, and a fully compensated interface are capable of showing such complex behaviors like the dynamic response measured with PIMM. Moreover, the Interacting Grain Model naturally exhibit the training effect which can be explained with irreversible changes of the antiferromagnetic domain structure during the first few reversals of the ferromagnet. Using PIMM simulation to investigate exchange biased bilayers, the training effect appears in a decrease of the resonance frequencies.

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