Spin dynamics in exchange-biased F/AF bilayers

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Abstract

The spin dynamics of the ferromagnetic pinned layer of ferro-antiferromagnetic coupled NiFe/MnNi bilayers is investigated in a broad frequency range (30 MHz-6 GHz). A phenomenological model based on the Landau-Lifshitz equation for the complex permeability of the F/AF bilayer is proposed. The experimental results are compared to theoretical predictions.

Key words: exchange coupling, frequency dependent susceptibility, Thin Films, Spin Dynamics

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1 Introduction

Exchange coupling between a ferromagnetic (F) and an antiferromagnetic (AF) layer has been extensively studied in last few years because of its importance for pinning the ferromagnetic layer in giant magnetoresistance spin-valve. MnNi seems to be a promising alloy for exchange coupling to NiFe due to its large exchange coupling field, its good corrosion resistance and its high blocking temperature [1]. Irreversible measurements (such as hysteresis loop) are commonly used to quantify the unidirectional exchange coupling in F/AF bilayers. Reversible experimental techniques, such as ac susceptibility and ferromagnetic resonance (FMR) and Brillouin light scattering (BLS) are also employed (for a review see [2]). These techniques lead to different values for the exchange field [3]. Most of the reversible techniques involve a constant frequency excitation and only a few papers [4] deal with the measurement of the complex susceptibility of F/AF bilayers in a broad frequency range. The aim of this paper is to probe, with the measurement of the complex permeability frequency spectrum, the exchange anisotropy of NiFe/MnNi bilayers with different Mn concentrations.

2 Experiments

Substrate\(Ni_{81}Fe_{19}280\text{Å}\)\(Mn_xNi_{100-x}800\text{Å}\) bilayers were grown on Corning Glass substrate by RF diode sputtering using a standard Z 550 Leybold equipment with a magnetic field of 300 Oe applied during deposition to induce an uniaxial anisotropy. The background pressure was lower than \(4 \times 10^{-7}\) mbar. Ni chips were homogeneously added to a four inches diameter Mn target in
order to get films in the Mn composition range 35-80 percent. The chemical homogeneity was verified by Electron Probe Micro Analysis (EPMA) on several points of the sample. The Mn composition variation is about one percent on the entire sample. After deposition, samples were annealed in a magnetic field of 1000 Oe, aligned with the easy axis of the film, at 300°C for 5 hours to induce the exchange field. The magnetic properties such as the saturation magnetization $M_s$ were obtained from magnetization loops (M-H loops) measured at room temperature using a VSM. The complex frequency spectra of the bilayers were measured from 30 MHz to 6 GHz using a broad band method. The method is based on the measurement, by a network analyser, of the reflection coefficient $S_{11}$ of a single turn coil loaded by the film under test [5]. Because of the topography of the applied ac field ($h_{ac}$) in the coil, the permeability can be measured for different orientations of the exciting field in relation to the in-plane anisotropy.

3 Results and discussion

We consider a F layer, with an uniaxial anisotropy field $H_k$ along the easy axis, submitted to an unidirectional exchange field $H_{ex}$, induced by the exchange coupling along the easy axis, and to an applied ac field $h_{ac}$ applied perpendicular to the easy axis. The initial susceptibility measured along the ac field is given by [6] $\chi = M_S/(H_{ex} + H_k)$. $\chi/M_S$ is the initial slope of the hysteresis loop when measured perpendicular to the easy axis. $H_{ex}$ is determined by the shift of the center of magnetization loop. $H_k$ is extracted from the M-H loops measured perpendicular to the easy axis (previous equation).

In $Ni_{81}Fe_{19}/Mn_xNi_{100-x}$ bilayers the exchange field depends strongly on the
Mn concentration and the growth conditions [7]. We have grown several bilayers, whose composition varies from 35 to 80 percent of Mn. Before annealing, for all the samples, only the soft magnetic behavior of NiFe was detected. After annealing and above 40 percent of Mn, the MnNi has gone through a Paramagnetic-AF phase transition. The M-H loops are shifted and typical of a F/AF coupling. The NiFe layer is still showing an in-plane uniaxial anisotropy.

We have measured $H_{k}^{mes}$ and $H_{ex}^{mes}$ on samples with different Mn compositions. The results are presented in Table 1. One can observe that the saturation magnetization of the NiFe layer decreased after annealing. This may be attributed to interfacial diffusion leading to the existence of an interdiffused AF ternary alloy FeMnNi at the NiFe-MnNi interface [7]. It can be seen that the values of the exchange field increase as a function of the Mn composition. The values of the anisotropy field $H_{k}^{mes}$ (up to 3 kA/m) are larger than those of the uncoupled annealed NiFe layer, and these values change significantly with the Mn composition.

We have measured the complex permeability spectra of the bilayers before and after annealing for the exciting field applied perpendicular to the easy axis. The results are presented in fig.1 for three samples and the major results for all the samples are presented in fig.2. Before annealing (as grown), there is no magnetic interaction between the NiFe and the MnNi layer. The permeability spectra are typical of damping by spin rotation processes in a NiFe layer [8]. For the annealed samples, when the exchange and the anisotropy fields increase, the level of the real part of the permeability $\mu'(0)$ at low frequency decreases and the roll off frequency increases. We can also observe that the imaginary part of the complex permeability $\mu''$ shows a lower resonance peak, a higher resonance frequency $f_{res}$ (up to 3.5 GHz) and a wider resonance peak
as the exchange field increases.

In a previous paper [9], we have presented an analytic calculation of the frequency dependent complex permeability tensor of a thin ferromagnetic film with uniaxial in-plane anisotropy, submitted to an external exciting field using the Landau-Lifshitz (LL) theory [10]. Using this calculation, we have obtained the components of the complex permeability tensor which are a function of $M_s$, the total effective field $H_{\text{eff}}$, the frequency $f$ of the exciting field and the phenomenological damping constant $\alpha$. The theoretical value of $\mu'(0)$ at low frequency is found to be $1+(M_s/H_{\text{eff}})$ and, as observed, the decrease of the saturation magnetization and the enhancement of the effective field ($H_{\text{mes}}^k + H_{\text{mes}}^{\text{ex}}$) lead to a reduction of the level of $\mu'(0)$. The resonance frequency $f_{\text{res}}$ is found to be $(1/2\pi) \times \gamma (H_{\text{eff}}(H_{\text{eff}} + M_s))^{1/2}$. In our samples the enhancement of $H_{\text{eff}}^{\text{mes}}$ is prevalent and lead to the enhancement of $f_{\text{res}}$. Fig. 3 shows an example of the comparison between theoretical and experimental complex permeability spectra when the exciting field is applied perpendicular to the easy axis. The results are presented for an as-grown sample and for one exchange-biased sample (NiFe/Mn$_{46}$Ni$_{54}$). For the other samples the fit parameters are presented in Table 1.

In a first step of calculations, the values the effective field ($H_{\text{mes}}^k + H_{\text{ex}}^{\text{mes}}$) and $M_{\text{mes}}^s$ are taken from static measurements and the value of the damping parameter is fitted. For the as-grown sample ($H_{\text{ex}}^{\text{mes}} = 0$), experimental results are in good agreement with the theoretical prediction as observed in fig. 3 (solid curve (a)). The value of the fitted damping parameter (0.012) is typical of the one obtained on a NiFe single layer [8]. For the exchange biased bilayers, the level of the permeability is in agreement with the theoretical values but the calculated resonance frequency is lower than the measured one.
(Fig.3 solid curve (a)). In a second step we have computed the complex permeability where the effective field was taken as a fit parameter ($H_{eff}^{fit}$). The result is presented in figure 3 (solid curve (b)). It can be seen that the experimental results are in good agreement with theoretical predictions. The fitted values of the effective field in the exchange biased bilayers are higher than those obtained from M-H loop measurements. Moreover, one can see that the broadening of the experimental spectrum of $\mu''$ is associated with the increasing of the damping parameter from 0.012 up to 0.035 (Table 1). It may be explained as follows. The experimental data should be not interpreted with a phenomenological model of fixed moment along the easy anisotropy direction. One should take into account a local variation of the exchange field at the F/AF interface. This local variation may be due to interdiffusion at the NiFe-MnNi interface. This complex magnetic structure at the interface may be grains of NiFe exchange coupled with antiferromagnetic NiFeMn "coating" on their surface [11]. These broadenings have been observed with FMR and BLS measurements and attributed to a relaxation mechanism based on two-magnon scattering processes due to the local fluctuation of the exchange coupling caused by interface roughness [12]. In conclusion, we have shown that it is possible to describe the magnetization dynamics of exchange biased bilayers with the LL theory. Effective fields are extracted from complex permeability spectra and are much larger than the ones obtained from a hysteresis loop measurements. The high values of the effective field associated with the enhancement of the damping parameter may be associated with interdiffusion in the bilayers.

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Table 1
Magnetic properties of the $NiFe/Mn_xNi_{100-x}$ bilayers. Magnetization and field units are in (A/m)

| $x$    | $M_{s}^{mes}$ | $H_{k}^{mes}$ | $H_{ex}^{mes}$ | $H_{eff}^{mes}$ | $H_{eff}^{fit}$ | $\alpha$ |
|--------|---------------|---------------|----------------|-----------------|-----------------|----------|
| as grown | 800×10^3     | 360           | 0              | 360             | 360             | 0.012    |
| 46     | 711×10^3      | 330           | 268            | 598             | 1010            | 0.027    |
| 58     | 662×10^3      | 975           | 624            | 1599            | 3600            | 0.03     |
| 68     | 537×10^3      | 3194          | 2082           | 5276            | 8500            | 0.035    |
Figure Captions

Fig. 1. imaginary (a) and real part (b) of the complex permeability spectra of As grown and annealed NiFe/MnNi bilayers with different values of the exchange field

Fig. 2. Experimental resonance frequency (●) and initial permeability $\mu'(0)$ (○) as a function of the Mn composition in NiFe/MnNi bilayers

Fig. 3. Measured and calculated $\mu''$ spectra of two NiFe/MnNi bilayers when the exciting field is applied along the hard axis; Solid line (a) simulated curve, (b) fitted curve
Figure 1

(a) 

As grown

$H_{ex} = 268$ A/m

$H_{ex} = 624$ A/m

(b) 

As grown

$H_{ex} = 268$ A/m

$H_{ex} = 624$ A/m
Figure 2

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The figure shows a graph with the x-axis labeled "% Mn" and the y-axis labeled "Resonance frequency (GHz)". The graph plots the relationship between the percentage of Mn and the resonance frequency. There are two curves indicated by different markers, one for 0 and another for 1. The y-axis is labeled with values ranging from 0 to 1000, with tick marks at intervals of 200 and 400, and with labels at 2 and 3 GHz. The x-axis ranges from 40 to 70, with tick marks at intervals of 5. The graph includes two distinct sets of data points for different samples, as indicated by the markers for 0 and 1.
Figure 3

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- As grown
- solid line : theory
- ○ : experiments

Annealed NiFe/Mn$_{46}$Ni$_{54}$

(a)

(b)