Magnetization reversal and spin dynamics exchange in biased F/AF bilayers probed with complex permeability spectra

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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. We show that the resonance frequencies, measured during the magnetization, are likewise hysteretic.

I. INTRODUCTION

Despite many theoretical and experimental studies in the last decade on and old phenomenon known as "exchange biasing", a full understanding of the exchange anisotropy at the interface between antiferromagnets (AF) and ferromagnets (F) is not clearly understood. One of the interesting observations is that irreversible measurements (such as hysteresis loop) and reversible techniques which imply small perturbations of the magnetization around equilibrium (AC susceptibility, ferromagnetic resonance, Brillouin light scattering, anisotropic magnetoresistance) seem to lead to different values of the exchange field. The second great challenge is to understand the mechanism by which the magnetization reverses in such systems. The aim of this paper is to probe by means of complex permeability spectra the exchange anisotropy of NiFe/MnNi bilayers and to study the magnetization reversal in such bilayers.

II. EXPERIMENTAL PROCEDURE

Substrate/Ni$_{50}$Fe$_{50}$ ($t_F$)/Mn$_{50}$Ni$_{50}$ ($t_{AF}$) bilayers were grown on Corning Glass substrate. After deposition, samples were annealed in a magnetic field of 1000 Oe, aligned with the easy axis of the (F) film, at 300°C for 5 hours to induce the exchange field. Detail of the sample preparation have been published elsewhere. The magnetic properties such as the saturation magnetization $M_s$ and the coercivity $H_c$ were obtained from magnetization loops (VSM) measured at room temperature. The coercivity of the biased NiFe layer was defined by the half of the shifted M-H loop width. The complex frequency spectra (CPS) of the bilayers were measured from 30 MHz to 6 GHz using a broad band method 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. 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. Among the prepared samples, we have chosen the ones with low values of the exchange biasing and coercive field essential for detecting a signal in the CPS measurements, all the results presented in this paper have been made on the same sample.

III. 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
\[ \chi = M_S/(H_{ex} + H_k). \]

$\chi/M_S$ is the initial slope of the hysteresis loop when measured perpendicular to the easy axis. $H^{meas}_{ex}$ is determined by the shift of the center of the magnetization loop. Following Xi and White, the susceptibility may be obtained from the hard-axis hysteresis loop by drawing a line tangent to the loop trough the origin intersecting the asymptotic limits of $M_S$ (point A). $H^{meas}_k$ is extracted from the M-H loops measured perpendicular to the easy axis (previous equation). Fig. 1 shows easy- and hard-axis loops for our bilayers. The extract values of $H^{meas}_{ex}$ and $H^{meas}_k$ are mentioned on this figure. In our samples the forward loop shows a slope, as

FIG. 1. Typical easy- and hard-axis hysteresis loops for a Glass/NiFe 52nm/Mn$_{50}$Ni$_{50}$ 80nm bilayer.
if the full magnetization take place progressively, while
the reverse loop is very very square which may be the con-
sequence of either coherent magnetization flip (such as in
monodomain particles) or the presence of high mobility
domain walls. We have measured CPS of the bilayers
before and after annealing for the exciting field applied
perpendicular to the easy axis. An example of the mea-
surement on a NiFe/MnNi bilayer is presented in Fig.2.

![Complex permeability spectra](image)

**Fig. 2.** Complex permeability spectra of a NiFe
52nm/MnNi80 80nm bilayer. (a) as-grown; (c) annealing
at 300°C for 5 hours (H = 950A/m; (b) as-grown with an
applied static field of 1550 A/m.

The as deposited state of the MnNi is non magnetic fcc
structure and 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 Fig.2(a) with a resonance frequency of µ' at
about 700 MHz\(^{10}\). In order to achieve an antiferromag-
netic tetragonal (fct) state, a high temperature annealing
was performed. For the annealed samples, the level of the
real part of the permeability µ'(0) at low frequency de-
creases and the roll off frequency increases fig.2(c). We
can also observe that the imaginary part of the complex
permeability µ'' shows a lower resonance peak, a higher
resonance frequency \(f_{res}\) (2.5 GHz) and a wider resonance
peak as the exchange field increases. We have submitted
to a static magnetic field whose amplitude is equivalent to
\((H_k^{meas} + H_{ex}^{meas} = 1550 A/m)\) the as-grown sample and
measured the CPS, the results are described on fig.2(b).
It is clear that such static field is not sufficient to reach
the high resonance frequency of the annealed bilayer and
the spectra are still very resonant.

A general description of the spin dynamics is often
made using the Landau Lifshitz (LL) theory, a useful
representation is the Gilbert form of the equation of mo-
tion:

\[
\frac{d|M|}{dt} = \mu_0 \gamma (M \wedge H) - \frac{\alpha \mu_0 \gamma}{M} (M \wedge (M \wedge H)) \tag{1}
\]

In a previous paper\(^{11}\), we have presented an analytic
calculation of the frequency dependent complex permea-
bility tensor of a thin ferromagnetic film with uniax-
ial in-plane anisotropy, submitted to an external exciting
field using the Landau-Lifshitz (LL) theory\(^{12}\). Using
this calculation, we have obtained the components of the
complex permeability tensor which are a function of \(M_s\),
the total effective field \(H_{eff}\), 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 \(1+(M_s/H_{eff})\) and, as observed, the decrease of the
saturation magnetization and the enhancement of the ef-
fective field \((H_k^{meas} + H_{ex}^{meas})\) lead to a reduction of the
level of \(\mu'(0)\). The resonance frequency \(f_{res}\) is found to be:

\[
\frac{1}{2\pi} \times \gamma (H_{eff}(H_{eff} + M_s))^{1/2}. \tag{2}
\]

In our samples the enhancement of \(H_{eff}^{meas}\) is prevalent
and lead to the enhancement of \(f_{res}\). Fig.3 shows the
comparison between theoretical and experimental com-
plex permeability spectra when the exciting field is ap-
plied perpendicular to the easy axis. In a first step of cal-
culations, the values the effective field \((H_k^{meas} + H_{ex}^{meas})\)
and \(M_s^{meas}\) are taken from static measurements and the
value of the damping parameter is fitted. For the as-
grown sample \((H_k^{meas} = 0, H_{ex}^{meas} = 360A/m, M_s^{meas} =
800kA/m)\) 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
(0.0135) is typical of the one obtained on a NiFe single
layer\(^{10}\). For the exchange biased bilayers \((H_{ex}^{meas} =
950A/m, H_k^{meas} = 600A/m, )\), the calculated resonance
frequency is lower than the measured one (Fig.3 solid
curve (b)). In a second step we have computed the com-
plex permeability where the effective field was taken as a
fit parameter \((H_{eff}^{fit})\). The result is presented in figure 3
(solid curve (c)). The best fit was obtained with values
\(H_{eff}^{fit}=4200 A/m\) and \(\alpha=0.03\). It can be seen that the
experimental results are in good agreement with theoret-
cal predictions. The fitted value of the effective field in
the exchange biased bilayers is three times higher than the
one obtained from M-H loop measurements. These
discrepancies may be due to the fact that M-H-loops in-
volve large applied static fields and the AC susceptibility
involves only a small perturbation of the magnetization
in is “natural” environment.
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 0.03. 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.\(^{13}\)

We have measured the CPS of the bilayers when submitted to a static magnetic increasing and decreasing field applied along the easy axis as in a hysteresis loop measurement. These measurements have been performed on both as-sputtered and annealed bilayers, the results are presented on Fig.4. For the as-sputtered sample (Fig.4(a)), the resonance mode frequency as a function of the magnetic field is fully reversible, with a minimum for $H = 0$, corresponding to the resonance frequency of 700 Mhz mentioned above. The frequency fit well by the equation\(^{(2)}\), where $H_{eff} = H_k + H$. $H_k$ and $M_s$ are taken from static measurement. For the annealed exchange biased sample, the curves split into two parts corresponding to the forward and reverse loop of the hysteresis curve, the frequencies are likewise hysteretic. This may be associated with the strong asymmetry observed in the hysteresis loop as presented in Fig.1. In the first magnetization reversal (forward), the frequency decreases then increases showing a minimum of 1.83 GHz for an applied field of about -800 A/m. This minimum is not well pronounced. In the recoil loop the frequency shows a sharp minimum of 1.89 GHz at -197 A/m. These minima correspond roughly to the different coercive fields in the forward and reverse magnetization direction. The evolution of the magnetization with the forward field could indicate a mechanism of coherent rotation, which would give a component of the magnetization along the hard axis, which is along the applied ac field. The may explain the decreased value of $f_{res}$ for the forward field. The frequency on the right side of the dip is fit very well by equation\(^{(2)}\), where $H_{eff}$ is taken from the effective field obtained from the previous calculation using the LL theory and the applied static field (i.e. 4200 A/m). This hysteretic behavior of the resonance frequency mode as been recently theoretically investigated by Stamps.\(^{14}\) The author attributes this behavior to different effective fields governing the frequencies of resonance for the forward and reverse field directions and obtains hysteretic resonance frequencies by including, in the energy, terms that take into account the coupling to both sublattices of the antiferromagnet and the formation of a planar wall.

**IV. 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 with the ones obtained from hysteretic loop measurements. The high values of the effective field are associated with the enhancement of the damping parameter. We have experimentally shown that in F/AF bilayers the resonance frequencies are likewise hysteretic when the bilayers are submitted to an forward and reverse static magnetic field. This behavior may be related to the strong asymmetry in the hysteresis loop.

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