Efficient dynamic magnetization measurement in a Py/Ru/Py trilayer

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Abstract. It has previously been shown that the quantity

\[ M_\mu = \frac{1}{4\pi^2} \sqrt{\frac{2}{\pi}} \int_0^\infty \left( \mu' (f) \right) df , \]

called the “efficient dynamic magnetization”, is a powerful tool for characterizing magnetic layers dedicated to microwave applications. It correlates the imaginary part of permeability and the magnetization distribution. This paper presents microwave permeability spectra of a Py/Ru/Py trilayer, which have been measured in the layer plane under an external magnetic static field \( H_{DC} \) using a single coil cell. The efficient dynamic magnetization versus \( H_{DC} \) was found to exhibit a significant decrease for \( 0 < H_{DC} < 5 \) Oe, and it is demonstrated that this decrease was induced by an optic mode excitation.

1. Introduction

Microwave applications such as magnetic recording write heads, broadband skin antennas, microwave filters, noise suppressors and radar-absorbing materials require the development of soft magnetic materials for high broadband permeability levels at elevated frequencies. However, it has been shown [1] that there exists a trade-off between permeability levels and the frequency according to

\[ \int_0^\infty \mu'' (f) df = k_4 \frac{\Pi}{2} (\gamma 4\pi M_s)^2 \]  

(1)

Where \( k_4 \) is a dimensionless factor associated with the distribution of the magnetization orientation of the sample. For anisotropic uniform soft thin films, \( k_4 = 1 \) and for isotropic materials, such as bulk sintered ferrites, \( k_4 \approx 1/3 \).

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For a thin layer, it has also been established that the above relation can be refined by taking into account experimental factors [2]. Once the sample presents no angular magnetic dispersion, the measured imaginary part of permeability along the hard axis is bounded according to

\[ \int_{0}^{\pi} \mu''(f) df = \frac{\pi}{2} N_{z} \left( \frac{\gamma 4\pi M_{s}}{2} \right)^{2} \left[ 1 - t - s + e \right] \]  

(2)

Here, \( N_{z} = 1 \) is the out-of-plane demagnetizing factor and \( t, s \) and \( e \) are the correcting factors for respectively the finite truncation, skin effect and measurement uncertainty. \( F \) is the maximum frequency measurement.

The quantities \( M_{\mu x}, M_{\mu y} \) and \( M_{\mu} \), known as the “efficient dynamic magnetizations” [2] have been considered along the \( x, y \) directions and in the sample plane:

\[ M_{\mu x} = \frac{1}{4\pi} \sqrt{\int_{0}^{\pi} \mu'_{x}(f) df} \quad M_{\mu y} = \frac{1}{4\pi} \sqrt{\int_{0}^{\pi} \mu'_{y}(f) df} \quad M_{\mu} = \sqrt{M_{\mu x}^{2} + M_{\mu y}^{2}} \]  

(3)

According to equation (1), for a single layer with a well-defined easy axis, \( M_{\mu} \) equals the static magnetization of the layer material. This assumption maintains its validity when a static field is applied for the condition \( H_{int} \approx H_{k} + H_{DC} < 4\pi M_{s} \) [2]. It remains available in the whole field range applied to the sample in the present experiments.

Figure 1 displays a plot of \( M_{\mu x}, M_{\mu y} \) and \( M_{\mu} \) for a 0.6-\( \mu m \) CoNbZr layer under a static field. As can be seen, \( M_{\mu} \) remained equal (within experimental errors) to the static layer magnetization deduced from Vibrating Sample Magnetometry, VSM.

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**Figure 1.** The efficient dynamic magnetization and saturation magnetization of a 0.6-\( \mu m \) CoNbZr layer.
A similar experiment was carried out with an artificial antiferromagnet made of a two Permalloy (Py) layers separated by a Ru spacer. The two Py layers were antiferromagnetically exchange-coupled by a RKKY interaction. Recently, it has been shown that such a system presents both optic and acoustic modes when a static in-plane field is applied [5-9]. The in-plane permeability under a static field generally exhibits a reduced $M_{µ}$ value at low field when the optic mode is excited. Moreover, when the static field is strong enough, the optic mode vanishes while $M_{µ}$ reaches $M_s$.

2. Experimental procedure

After first depositing a 5-nm Ta sub-layer to induce a Py texture with good softness properties, a Py(60 nm)/Ru(0.6 nm)/Py(60 nm) trilayer was sputter-deposited on 9 mm x 9 mm flat glass substrates. This was followed by addition of another 5-nm Ta layer on the top as a capping layer. The in-plane edge directions were respectively designated X and Y.

Static magnetic properties were investigated using a Vibrating Sample Magnetometer (VSM). The microwave permeability measurement setup was based on the impedance measurement of a shorted microstrip line with the ferromagnetic sample between the ground plane and the conducting strip [3]. The microwave permeability spectra were measured in the range [10 MHz ..6 GHz] along the X and Y directions of the sample, as shown in Figure 2. A Helmholtz coil was used to induce an external magnetic static field, $H_{DC}$, parallel to the X sample direction. $H_{DC}$ was swept from 0 to 100 Gauss.

Figure 2. The setup for the permeability measurement: a single coil cell under a static field. $M_{µ}^X$ and $M_{µ}^Y$ were respectively measured in configurations (a) and (b).

3. Results and discussion

Experimental and simulated hysteresis loops of the artificial antiferromagnet Py/Ru/Py have been plotted in Figure 3.a. As can be seen, the hysteresis loop exhibited a singular point and the saturation magnetization was equal to 9560 G. The fitting line in Figure 3.a was obtained with a macro-spin model [8] for which the magnetization was considered uniform in a same layer. The total energy (equation 4) - which includes the Zeeman energy, anisotropic energy and exchange-coupling energy - is minimized with respect to the angle of the magnetization of the top and bottom layers.

$$E_T = -M_s H_{DC} \cos(\theta_1 - \theta_H) + t_2 \cos(\theta_2 - \theta_H) + K_u \left[ t_1 \sin^2(\theta_1 - \theta_{K1}) + t_2 \sin^2(\theta_2 - \theta_{K2}) \right] - J_1 \cos(\theta_1 - \theta_1) - J_2 \cos^2(\theta_1 - \theta_2)$$  

(4)

Here, $E_T$ represents the total energy to minimize; $t_1$ and $t_2$ are the thicknesses of the two layers; $\theta_H$, $\theta_1$ and $\theta_2$ are the angles between $H_{DC}$, the first- or second-layer magnetization and the X axis of the sample. $\theta_{K1}$ and $\theta_{K2}$ are respectively the angles between the easy axes of the first and second layer, and...
the sample’s X axis. $K_a$ is the anisotropy constant, and $M_s$ the magnetization saturation. Finally, $J_1$ and $J_2$ are the bilinear and biquadratic coupling parameters of the RKKY interaction through the Ru layer.

A good agreement between experiment and simulation was obtained with $\theta_{K1} = \theta_{K2} = 15^\circ$, $K_u = 760$ erg/cm$^3$, $J_1 = 0.06$ erg/cm$^2$ and $J_2 = 0.018$ erg/cm$^2$. The $J_1$ and $J_2$ exchange-coupling values were consistent with data from the literature [5, 6, 7, 9]. The magnetization orientation of each layer is presented in Figure 3.b. At zero field, the two magnetizations were in anti-parallel states. In the range [-5 Oe ..+5 Oe], there was a spin-flop transition where the two magnetizations were forced to adopt a canted configuration. Then, the two magnetizations slowly tended toward the magnetic field direction, to finally reach a saturated state at 40 Oe.

![Figure 3](image1)

**Figure 3.** (a) Experimental and simulated VSM hysteresis loops. (b) The variation of the magnetization orientation.

Figure 4 illustrates the efficient dynamic magnetization $M_{µ}$ versus the static field $H_{DC}$. As can be seen, the curve exhibited a drop at low field. Moreover, there was a discrepancy between the static $M_s$ value and $M_{µ}$; this gap was observed when the Py magnetizations were in canted configuration ($H_{DC} < 5$ Oe). For higher values of external static field, the quantity $4 \pi M_{µx}$ decreases because the magnetization turns up to be aligned to the external static field at saturation. So, the dynamic response along x axis is almost zero rather than it’s maximum along y axis. One can moreover see that $4 \pi M_{µ} = 8700$ G when $H_{DC} = 0$ Oe and reached 9700 G when $H_{DC} > 5$ Oe.

![Figure 4](image2)

**Figure 4.** The efficient dynamic magnetization and saturation magnetization of the Py/Ru/Py trilayer.
Figures 5.a and 5.b present the imaginary part of permeability spectra and the deduced resonance frequencies. One can observe three behaviors. At low field (< 3 Oe), the resonance frequency decreased from 1.4 GHz to 1.26 GHz. At high field (> 6 Oe), a single peak with a resonance frequency increasing with the static field could be evidenced, in accord with an \( F \mu^2 \sim H_{DC} \) law. In between, two resonance peaks were observed.

This feature has previously been evidenced in artificial antiferromagnetic trilayers [5-9], and is typical of the coexistence of an optic and an acoustic mode. Such optic and acoustic modes have also been observed in simple systems, such as Co-Py bilayers [4].

As shown in figure 5.b, the optic mode became excited at low field while its acoustic counterpart was excited at high field. The pure optic mode was obtained when the two ferromagnetic layers oscillated in phase in the out-of-plane direction and in opposite phases within the sample plane. One should notice that the observed resonance could not be a pure optic mode since the resulting permeability measured in the sample plane was not perfectly compensated. However, it generated the observed drop in efficient dynamic magnetization at low field (see figure 4). This discrepancy can be corrected by taking into account the out-of-plane efficient dynamic magnetization component \( M_x \) (see equation 5). This component is usually neglected and can be enhanced by the optic mode.

\[
M_x = \sqrt{M_y^2 + M_z^2 + M_x^2}
\]  

4. Conclusions
The determination of the efficient dynamic magnetization is a powerful tool for characterizing magnetic samples dedicated to microwave applications. It has been successfully carried out with an artificial antiferromagnetic trilayer where optic and acoustic modes were excited through a static field. A decrease of the dynamic magnetization was evidenced when measured in the sample plane at low field induced by the optic mode.

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