Giant magnetoimpedance in FM/SiO$_2$/Cu/SiO$_2$/FM films at GHz frequencies

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Available online 4 March 2008

Abstract

We study the magnetic properties at high frequency of new structures of the tri-layer samples. The magnetoimpedance effect was analyzed in FM/i/Cu/i/FM sandwiched layers, where the ferromagnetic layer (FM) is, in fact, a multilayered film [F (10 nm)+Cu (1 nm)]$^{50}$ and F is the amorphous ferromagnetic alloy Fe$_{73.5}$Cu$_{1}$Nb$_{3}$Si$_{13.5}$B$_{9}$ and i is an isolating layer produced by magnetron sputtering. The effect of, both, the probe current frequency (in the range 10 MHz–1.8 GHz) and the dimensions of the magnetic and non-magnetic layers of the MI response were investigated. A comparison between samples with and without the isolating layer is discussed. MI ratios of 220% were obtained for samples at 180 MHz with a ferromagnetic and Cu width layers of 2 and 1 mm, respectively.

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PACS: 75.50.Kj; 75.70.Cn; 77.80.Dj

Keywords: Magnetoimpedance; Multilayer; Film

1. Introduction

It is already known that the complex impedance $Z = R + jX$ value of a ferromagnetic material is varied when it is submitted to an AC and DC magnetic field, simultaneously. This variation is connected to the change of the magnetic permeability for different frequencies and magnetic field intensities. This is the called magnetoimpedance (MI) effect that has been intensively studied in order to apply it in, for example, magnetic field sensors [1] and the detection of biomolecules [2]. In the last years, the interest in tri-layer structured samples has been increased [3,4] due the possibility of obtaining higher MI variation for lower frequencies, if compared with the results obtained for a single-layer samples. In tri-layer structured samples, the insertion of a non-magnetic metallic layer, separating the two ferromagnetic layers, increases considerably the conductivity of the sample, which is an important parameter for the study of MI. Another main point for this structured sample is the way that the internal fields act inside the sample, being possible the appearance of the magnetoinductive effect. The calculus of the impedance for a wide range of frequencies for these structured samples was already performed by Panina and Mohri [5] based on boundary problems of classical electrodynamics. The analysis was made as a function of some parameters such as the ratio between the conductivity of the ferromagnetic and the metallic layers, the width of the tri-layer, and the ratio between the thickness ($t_1$ and $t_2$), etc. The general expression for the impedance in tri-layer structured samples is given by

$$\frac{Z}{R_{dc}} = \left(\eta_{m}\eta_{F}\right)\frac{\text{Coth}(\eta_{m}\sigma_{2}/\sigma_{1}\mu)\text{Coth}(\eta_{F}) + (2\eta_{m}/k_{1}t_{1})}{\text{Coth}(\eta_{m}\sigma_{2}/\sigma_{1}\mu) + (2\eta_{m}/k_{1}t_{1})\text{Coth}(\eta_{F})},$$

(1)
where the variables in Eq. (1) are:
\[
\eta_m = \frac{k_1 t_1}{2} \left( \frac{\sigma_1 \mu_1}{\sigma_2} \right), \quad \eta_f = k_2 t_2, \quad k_1 = \frac{(1 - i)}{\delta_1}, \\
k_2 = \frac{(1 - i)}{\delta_2}, \quad \delta_1 = \left[ 2 \pi \sigma_1 \omega \right]^{-1/2}, \quad \delta_2 = \left[ 2 \pi \sigma_2 \omega \mu \right]^{-1/2}. \tag{2}
\]

The aim of this work is to study the MI effect in samples with a new structure. Differently than in others works that study ferromagnetic single layer composing the tri-layer, this work uses a ferromagnetic/metallic multilayer to form the tri-layer. It has already shown in previous work [6] that the FeCuNbSiB/Cu multilayers present a high magnetic permeability with low hysteretic loss. It is noticed that multilayer samples increase the electrical conductivity. With that, the ratio \( \sigma_1/\sigma_2 \) is reduced and, consequently, there are changes in the MI\textsubscript{max} vs. frequency behavior. Besides, there is possibility of controlling the position of the maximum values of MI vs. frequency.

2. Experimental

The samples investigated in this work have the form FM(500 nm)/i/Cu(1000 nm)/i/FM(500 nm). The FM part of the tri-layer consist in a multilayer of [Fe\textsubscript{73.5}Cu\textsubscript{1}Nb\textsubscript{3}Si\textsubscript{13.5}B\textsubscript{9} (10 nm)/Cu (1 nm)] \times 50 and i represent a sample with or without SiO\textsubscript{2} (250 nm) layer (Fig. 1). The films were deposited onto a glass substrate with a buffer of Ta by magnetron sputtering. The sputtering chamber base pressure was 4 \times 10^{-7} Torr and the deposition was made under a 5.25 mTorr Ar pressure. The deposition rate was 155.4 Å/min (65 W-RF source), 89.4 Å/min (25 mA—DC source) and 108 Å/min (50 mA—DC source) for the targets of the Fe\textsubscript{73.5}Cu\textsubscript{1}Nb\textsubscript{3}Si\textsubscript{13.5}B\textsubscript{9}, Cu and Ta, respectively. Low-angle X-ray was used for this calibration in 200 Å samples, approximately. Masks were utilized during the deposition in order to give form to the sample. The films were grown with the substrates in movement onto gun, with the purpose of having a better uniformity, and under a 100 Oe magnetic field to induce anisotropy. In Fig. 1, the tri-layer structure and magnetic field is shown. These samples have a width metallic layer (\( W_m \)) variable of 0.25–1.00 mm and a length of the 16 mm. The multilayer components of the tri-layer have a fix length 12 mm and width (\( W_F \)) of the 4 and 2 mm this difference between the length possibility the electrical contact. The magnetic measurements were performed by vibrating sample magnetometry (VSM) in the ±100 Oe magnetic field range. High-angle X-ray measurements verified the amorphous character of the samples (not show here). The MI measurements were performed with an impedance analyzer HP43296B and an HP43961A RF adapter. The measurement was performed in a frequency, \( f \), range from 100 kHz to 1.8 GHz. The MI ratio is defined here as MI\% = 100 \times [Z(\text{H}) - Z(\text{H}_{\text{max}})]/Z(\text{H}_{\text{max}}).

3. Results and discussion

As shown in Ref. [6], the multilayer samples exhibit a very strong anisotropy induced by the magnetic field applied during the deposition process. This feature is observed through the high MI effect response. The magnetic properties do not have a considerable change when the multilayer forms the tri-layer structure. For a magnetic system with the DC magnetic field and \( I_{\text{ac}} \) (alternating current) perpendicular with respect to uniaxial anisotropy, a double peak structure is characteristic [7]. Comparing the two structures, with and without i insulating layer, a double peaks characteristic is observed.
for low frequencies. In Fig. 2, $Z$ vs. $H$ curves for both samples structure with $W_f = 4$ mm and $W_m = 1.00$ mm are displayed by a 10 MHz frequency. This behavior reflects the static magnetic property (magnetization curves) that shows a well-determined anisotropy. The $M_{I\text{max}}$ vs. $f$ values in 10 MHz–1.8 GHz frequency range is shown in Fig. 3. Measurements with frequencies smaller than 10 MHz give rise to a small signal/noise ratio (not shown here).

In Fig. 3, a considerable change in the $M_{I\text{max}}$ behavior can be noticed, when the insulating layer was added in order to isolate the metallic layer form the multilayer. The samples with SiO$_2$ insulating layer have shown an intense peak with MI ratio of 125% at 600 MHz for $W_f = 4$ mm and $W_m = 1$ mm, while the sample without insulating layer presents lower $M_{I\text{max}}$ ratios, caused by the lower $\sigma_1/\sigma_2$ value. This value influences considerably in the impedance value, as observed in Eq. (1). Furthermore, a plateau of about 50% has been observed for a large frequency range 10–300 MHz.

From this point, the results for the samples with an insulating layer with $W_f = 2$ mm and different $W_m$ values are shown and discussed. For frequencies where the FMR effect is observed, the displacement of the peaks as a function of the field is noticeable and peculiar features of the $R$ and $X$ behavior as a function of the frequency become considerable, as shown in Fig. 4. In this figure, the characteristic behavior of the FMR with the real part having a maximum value and the imaginary part passing by zero simultaneously, at a field of 24 Oe for different $W_m$, can be seen. The curves just illustrate that the FMR is verified in this samples. It must be emphasized that the maximum values of MI ($M_{I\text{max}}$) occurs in different magnetic field and frequency values for samples with different $W_m$, as will be seen in Fig. 5. It is a consequence of the fact that, when the FMR is present, there is a

![Fig. 3. M_{I\text{max}} vs. f for two structured samples.](image)

![Fig. 4. Real and imaginary parts of the impedance in frequency function are related in this figure for different W_m for a magnetic field of 24 Oe this figure show the FMR characteristic.](image)

![Fig. 5. M_{I\text{max}} vs. f for all W_m values for this work. The M_{I\text{max}} is 220% for samples with W_m = 1.00 mm. If possible, verify the plateaus for W_m = 0.75 mm sample.](image)
well-defined frequencies, there is an overlap that gives rise to the plateau. For width $W_m = 0.25$ mm, the overlap was not so considerable so as to give rise to two peaks. For these samples, the increase of $W_m$ width originates considerable variation in the internal field distribution and, consequently, in the induction of transverse anisotropy with respect to the main axis of the sample during the MI measurements, resulting in a decrease of the FMR frequency.

4. Summary

In the present work, it was observed that the structured samples with insulating layer, used in order to isolate the metallic layer from the multilayer, display higher $M_{\text{Imax}}$, $i_f$ compared with the samples without the insulating layer. The existence of the plateaus gives us the possibility of application of this sample structure in magnetic sensors with a good efficiency and sensibility in a large frequency range. Besides, through the change of the structure, with or without SiO$_2$ insulating layer, it was possible to control the $M_{\text{Imax}}$ position with respect to the frequency, an important feature that can be applied in sensors that requires a well-defined frequency value.

References