A study of the magnetic permeability of ferromagnetic thin films for evaluating the GMI effect

Driton Rustemaj and Debashis Mukherjee
Engineering Design Department, FESBE, LSBU, London, UK.

Abstract - An investigation of the Giant Magneto Impedance (GMI) effect on planar thin films of soft ferromagnetic material with different compositional ratios has been reported. The report contains the background theory leading to the explanation of the underlying Landau-Lifshitz equation for evaluating the magneto-impedance behavior of the material, in relation to the relevant measurement parameters, i.e. the damping parameter and the resistivity. The findings of this study have been useful for calculating complex magnetic permeability, and the ferromagnetic resonance frequency of soft ferromagnetic materials. The results of the investigation are in good agreement with the previously published data on the magnetic permeability of the soft ferromagnetic materials, demonstrating the validity of the model within the frequency range that has been under investigation.

Keywords: GMI effect, Soft Ferromagnetic materials, Complex permeability constant, Magnetic sensors, Nano-magnetic devices

1 Introduction

The Giant Magneto-Impedance (GMI) effect [1] in soft ferromagnetic materials has attracted significant interest for multimedia applications, such as high sensitivity nano/micro magnetic sensors, filtering devices, and microwave communication circuits [2]. The effect can be attributed to a change in the impedance of the material under the influence of an external magnetic field. It is caused due to the penetration of the field through the skin of the soft-ferromagnetic material. The depth of penetration (δ) depends on the angular frequency (ω=2πf) of the ac current flowing through the material, being governed by the expression:

\[ \delta = \sqrt{\frac{2\rho}{\omega \mu}} \]  

where \( \rho \) is the resistivity of the material and \( \mu \) is the complex magnetic permeability of the material which is expressed in the form \( \mu = \mu' + j\mu'' \).

A variation of the frequency dependent \( \delta \) in soft-ferromagnetic wires and thin films causes the eddy current losses [3], which in turn decrease the GMI effect in the material. These losses occur due to the existence of magnetic domain structures, which are dependent on the method of growth and related processing techniques [4]. The \( \mu \) is the most convenient parameter to describe the GMI-effect which in theory, at high frequencies (up to few GHz), can be attributed to the changes mainly caused by the motion of the magnetic moments [5,6].

Theoretically, the GMI effect can be extracted, through obtaining \( \mu \) by simultaneously solving the already established Maxwell’s equations in the form of wave equations, and the linearized form of dynamic equation of motion or Landau-Lifshitz equations [1]:

\[ \nabla^2 H - \frac{\mu_0}{\rho} \frac{\partial H}{\partial t} = \frac{\mu_0}{\rho} M - \nabla \cdot \operatorname{div} M \]  

\[ \frac{dM}{dt} = -\gamma M \times H_{\text{eff}} + \alpha \frac{M \times \frac{dM}{dt}}{M} \]  

where \( H \) is the magnetic field, \( \mu_0 \) is permeability in vacuum, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) - the Gilbert damping parameter, \( M \) - the magnetization vector and \( H_{\text{eff}} \) is the dc component of the effective field [7, 8].

The analytical solution of these equations is far from straightforward and has only been obtained previously by several authors under simplifying assumptions [7, 8] such as:

i. an in-plane uni-axial anisotropy
ii. the initial magnetisation is uniform

iii. the film thickness is very small and

iv. the only existence of dynamic demagnetization field.

Tanaka et al [9] has, for example, shown the solution to be of the form:

\[
\mu'(\omega) = \mu'(\omega) - j\mu'(\omega) = 1 + \frac{\gamma 4\pi M_s}{\tilde{H}_k + j\alpha\omega} \times \\
\left[ 1 + \frac{\omega^2}{(\gamma\tilde{H}_k + \gamma 4\pi M_s + j\alpha\omega)(\gamma\tilde{H}_k + j\alpha\omega) - \omega^2} \right] \quad (4)
\]

where \( H_k \) and \( M_s \) are the anisotropic field and the saturation magnetization, respectively. They used this equation to find the real and imaginary parts of the magnetic permeability. We have used the same equation in our calculation with an extended frequency range of up to 10 GHz and in combination with studying the effects of the variation of the damping parameter and the resistivity. This enabled us to simulate the waveforms of the magnetic permeability for various sample dimensions and composition, with a view to exploring device structures for a range of applications.

The evaluation of the GMI effect is involved with the measurement of the \( \mu \) value in the element, which is primarily dependent upon its size, geometry and the composition for both homogeneous and inhomogeneous types. The measurement is also influenced by the fabrication method and the associated annealing process, which can affect the internal alignment of the easy axes of the magnetic material. There are other numerous factors depending on the type of materials that have to be considered in evaluating the GMI effect.

When an ac current \( I = I_0 e^{-j\omega t} \) flows through the planar thin film, it brings about changes in its magnetic domain structure, causing a variation in the anisotropic field within it. This will directly affect the permeability value, which will also be influenced by the strength of the external magnetic field and the frequency of the current [10].

2 Numerical simulation and discussion

Figure 1 shows the frequency dependent variation of the complex permeability values due to Tanaka et al [9]. Their calculations took into account the thickness of the sample and a fixed value of 0.015 for the Gilbert damping constant \( \alpha \), as can be seen in the diagram.
The complex permeability spectra for the given values of ferromagnetic thin film ($\alpha = 0.01$)

In obtaining these results, the programming code was written in Matlab, using the appropriate parameter values, taken from Tanaka et al [9] and converted for SI system compatibility. As expected, the figures show good similarity with the plot of figure 1 up to a frequency of about 7 GHz. The test for an alternative damping constant $\alpha$ (0.01), was also carried out in this study in compliance with the published experimental data. The initial value of the real part of the magnetic permeability corresponding to the lower end of the frequency [8, 9], is also strikingly similar to that in figure 1 with a value of the order of 100. As can be seen in the diagrams of figure 2, the damping factor $\alpha$ inversely affects the magnitudes of both the real and imaginary parts of the magnetic permeability. The effect on the bandwidths around the Ferro-magnetic resonance (FMR) frequency is also similar, although appearing to be relatively more pronounced for the imaginary part.

3 Conclusions

Numerical calculations have been done using Matlab, to evaluate the complex permeability of Ferromagnetic thin films using published data and theoretical work.

The values of the real and imaginary parts of the complex magnetic permeability have been predicted through assuming damping parameter ($\alpha$) values of 0.01 and 0.015 with a frequency range of up to 10 GHz. The results show good agreement with previously published results, both in terms of the shape of the plots and the ranges of values obtained for the FMR. The effect of the variation of resistivity was also studied. The results provide a useful basis for predicting the GMI effect of thin films for various applications.

4 References