Domain wall permeability limit for the giant magnetoimpedance effect

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The magnetoimpedance (MI) effect is based on the change of inductance and resistance under the effect of an external magnetic field. In bulk homogeneous wires or ribbons these two components of the impedance are related to the penetration depth of the electromagnetic field in the material. From simple considerations it is shown that the maximum MI ratio is then proportional to the square root of the relative permeability of the material. That limit is reached for frequencies at which the penetration depth is of the order of the transverse dimensions of the sample. At low operating frequencies, typical of thick geometries, the permeability is limited by the microeddy currents associated with domain wall displacements. The permeability relaxation equivalent to these local eddy currents can be calculated and used in the classical expressions for MI. The real part of the permeability is highly reduced at the relaxation frequency and gives rise to a decrease of the inductance, while the imaginary part contributes to the resistance, with a maximum at the same frequency. [DOI: 10.1063/1.1451805]

Magnetoimpedance (MI) is the change of the impedance experienced by an ac current flowing through a magnetic material when an external dc magnetic field is applied. This effect is quite promising for tiny field sensors with high sensitivity and high response. In the last years a lot of works have been published on MI from both a theoretical and an experimental approach.[1–3]

Theoretical studies are based on the early works by Lord Rayleigh, Kittel, and others[4,5] about the frequency dependent impedance (Z) of a wire or sheet. From Maxwell equations one can calculate the dependence of the impedance on the magnetic permeability. This model, known as the classical model, gives the following expression for impedance for a sheet of infinite width and length, and of thickness $2a$, when an ac current of angular frequency $\omega=2\pi f$ flows through it:

$$\frac{Z}{R_{\mathrm{dc}}}=\sqrt{j}\,\theta\coth(\sqrt{j}\,\theta), \tag{1}$$

where R_{dc} is the dc resistance, $j=\sqrt{-1}$, and $\theta=a\sqrt{\sigma\mu_{\mathrm{dc}}\omega}=\sqrt{2}a/\delta_s$, δ_s being the skin depth, σ the conductivity, and μ_{dc} the low frequency transverse permeability. A similar expression holds for wires, where Bessel functions are involved. The external bias field changes the permeability, and thus the impedance of the film. The maximum magnetoimpedance ratio is defined as MI $(\%)=100\ (Z_{\max}-Z_{\min})/Z_{\min}$, where $Z_{\max}$ is the maximum value of impedance obtained for the maximum transverse permeability that is obtained at $H_{\mathrm{dc}}=0$ or around $H_{\mathrm{dc}}=H_k$, depending on the dominating magnetization process in the sample. $Z_{\min}$ is the minimum value of impedance obtained for $\mu\approx\mu_0$ at very high fields when the sample is magnetically saturated.

There is an important difference between the theoretically calculated MI and that experimentally found. The maximum MI ratio can be calculated with Eq. (1), using the high frequency asymptotic form of coth(x), as

$$\mathrm{MI}(\%)=100\left(\frac{Z_{\max}}{Z_{\min}}-1\right)\approx 100(\sqrt{\mu_r}-1). \tag{2}$$

So, even a modest permeability like $\mu_{\mathrm{dc}}=1000\mu_0$ should give a MI ratio of about 3000%, while MI experiments yield values of several hundreds percent in the most outstanding results.[6–8] Also, it is not unusual to find big discrepancies between measured MI ratios in samples of very similar characteristics and compositions. So it seems clear that using an expression as simple as Eq. (1) is not a very accurate procedure.

There are a number of phenomena that have been proposed to explain these discrepancies. For example, taking into account ferromagnetic resonance or spin relaxation effects via the Landau–Lifshitz equation results in a theoretical limit for the maximum value of MI ratio.[9] However, this limit appears at high frequencies, in the GHz range, and is of the order of 10^4%, so it cannot explain the small experimental MI ratios. Another approach to understand the MI values has been to derive the permeability from MI measurements.[10–12] For amorphous wires, strong permeability relaxation is found at frequencies around 100 kHz as a result of wall movement damping. This, however, neglects the classical skin depth influence, and then is valid only at low frequencies.

In this article we propose to study the domain wall relaxation and skin depth effects together because both have a great importance and must be taken into consideration when studying the MI effect. There have been several experimental[11,12] as well as theoretical[13–15] works about domain wall displacement influence on MI, but to our knowledge, the combination of wall relaxation and skin effect is not usually considered.

The equation of motion of a domain wall, when it is excited by an ac magnetic field $H\exp(j\omega t)$ can be written as

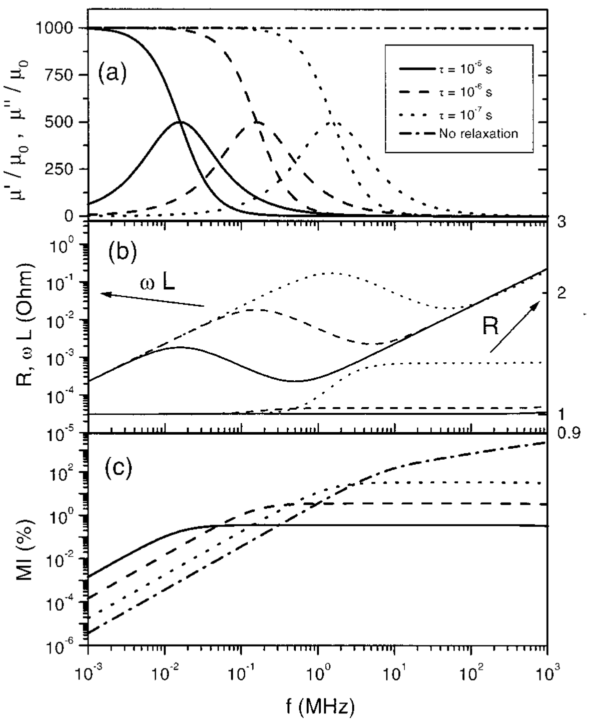

FIG. 1. Complex permeability spectra (a), real part of impedance (b, right axis), imaginary part of impedance (b, left axis) and magnetoimpedance ratio (c), computed for an amorphous ribbon considering a domain wall relaxation time τ of 0.1, 1, and 10 μs.

$$m\omega^2 z - \beta\omega j z - \alpha z = -2\mu_0 M_s H, \tag{3}$$

where z is the wall displacement, m is its effective mass, β is a damping parameter that can account for different mechanisms, and α is the restoring constant. Surface tension has been neglected in this equation. From Eq. (3), permeability can be calculated, resulting in a complex apparent permeability $\mu^* = \mu' - j\mu''$:[16]

$$\begin{cases} \mu' = (\mu_{\mathrm{dc}} - \mu_0)\dfrac{1}{1+\tau^2\omega^2} + \mu_0, \\ \mu'' = (\mu_{\mathrm{dc}} - \mu_0)\dfrac{\tau\omega}{1+\tau^2\omega^2}, \end{cases} \tag{4}$$

where $\tau = \beta/\alpha$. This relaxation time τ represents a general relaxation parameter that accounts for the delay of the domain wall displacement with the exciting field as frequency increases. This apparent permeability [Fig. 1(a)] can be introduced in the classical impedance expression [Eq. (1)] as a complex magnitude to estimate the effect of wall relaxation in impedance. In some cases it is possible to calculate directly the contribution of the microeddy currents produced by domain wall displacements in magnetoimpedance,[14,15] but this requires to specify a particular domain structure in the sample and to make some assumptions about the wall dynamics. In this work we are more interested in describing the effect of domain wall relaxation in a more general way, so the procedure used is completely general.

In our calculation, we have used $\mu_{\mathrm{dc}} = 1000\mu_0$ as the maximum permeability value, $\rho = 115\ \mu\Omega$ cm, and a thickness $2a = 20\ \mu$m. These values are typical for an amorphous ribbon. The results are presented in Fig. 1. Without relaxation the MI limit is reached at about 1 GHz. As it is expected, the effect of wall relaxation on magnetoimpedance is quite remarkable. For high values of the relaxation time ($\tau = 10\ \mu$s) the wall is unable to follow the alternating field even at low frequencies, the walls are completely damped before the impedance starts to rise, and the MI effect does not appear (or it is very small). For small τ ($\approx 1\ \mu$s), the walls can follow the alternating field up to frequencies around the MHz, so when the wall relaxation manifests, the MI has already appeared. In this situation, the decrease of μ'' above its maximum (that would decrease the real part of the impedance) is compensated by the standard eddy current increase of Z', and in the model used here, both compensate to give a frequency independent MI plateau at a few MHz, as found in experimental measurements (see for instance the inset of Fig. 2 in Ref. 7). Finally, we note that MI at low frequencies is increased by relaxation as a consequence of the μ'' contribution to resistance.

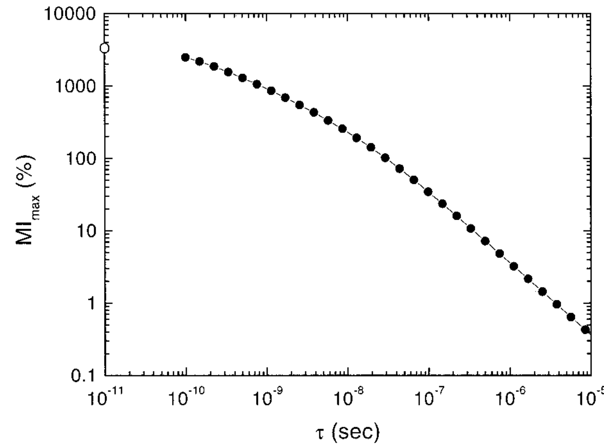

FIG. 2. Maximum value of magnetoimpedance ratio as a function of the wall relaxation time. For very small times the curve tends to the maximum value obtained without considering relaxation, represented with an open circle in the figure.

However, the most remarkable effect of wall relaxation is the dramatic reduction of the maximum MI ratio as compared to MI computed without relaxation [Fig. 1(c)]. MI falls several orders of magnitude when relaxation is considered (Fig. 2). This can easily explain the small values of MI that are usually measured. Indeed, other effects such as magnetic rotation damping, external inductance, etc. have to be taken into account for a more complete description of the effect.

In summary, we have calculated with a simple model the effect of domain wall relaxation on the magnetoimpedance effect, showing that it can be very important and should be kept in mind in MI analysis.

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