High-Frequency Giant Magneto-Impedance in Co-Rich Amorphous Wires and Films

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The giant magneto-impedance (GMI) effect is considered for the case of high frequencies, when domain wall motion is strongly damped and magnetization proceeds mainly *via* the rotation of magnetic moments. The theoretical approach is based on the skin effect in a magnetic conductor with the rotational permeability tensor. In the case of a strong skin effect, the rotational mechanism of GMI in a transverse magnetic structure is found to result in an impedance change of as much as 100% in magnetic fields of the order of the anisotropy field. The high-frequency response of impedance is generally larger than that associated with the magnetization *via* the wall movement. The theoretical results agree satisfactorily with existing experimental data obtained for Co-rich amorphous wires and films.

Key words: skin effect, magneto-impedance, magnetization rotation, amorphous wire, amorphous film

1. Introduction

Giant magneto-transport phenomena have attracted much interest because of their importance for applications in micro-magnetic sensors and magnetic heads for recording. In the case of giant magnetoresistance, although the nominal values can be very large ($\sim 50\%$ in multilayers^{1), 2)}), the sensitivity to the field is relatively low and does not exceed $1\%/Oe$. On the other hand, recently a giant and sensitive magneto-impedance (GMI) effect has been found in CoFeSiB amorphous wires and ribbons.^{3)–5)} In these materials under the application of a longitudinal magnetic field, a typical response of a complex impedance, $Z = R + jX$, including both resistance, R , and reactance X , is about $10\%/Oe$ in a MHz frequency region. The GMI effect has a classical electromagnetic origin, owing to the skin effect in conjunction with the transverse magnetization (with respect to the current direction).^{6), 7)} Because of the skin effect, in a high frequency region the impedance depends on the penetration depth and, hence, on the transverse magnetic permeability, which can be a sensitive function of an external field.

The GMI effect is most sensitive in the case of a soft magnetic conductor with a transverse magnetic structure (domain walls are perpendicular to the current and external field direction, as shown in Fig. 1). At moderate frequencies and an external field H_{ex} less than the

Fig. 1 Transverse magneto-impedance effect in a wire (a) and in a film (b).

anisotropy field H_k the transverse magnetization proceeds mainly *via* the domain wall motion. The corresponding transverse permeability is large, but quickly decreases with the application of the longitudinal field. Then the absolute value of Z also decreases. For an example, in FeCoSiB nearly zero magnetostrictive amorphous wires, this decrease in Z is as much as 40–60% for fields of 3–10 Oe. This case has been investigated in detail in refs. 4,6,7. For higher frequencies, when the domain walls are nearly damped, the moment rotation dominates. In this paper we discuss the rotational mechanism of the GMI effect. For a transverse magnetic structure, the external field stimulates the rotational processes while $H_{ex} < H_k$ and the rotational permeability has a maximum at $H_{ex} = H_k$. Then, as the frequency is increased, this maximum appears in the impedance-field dependence. Such behavior of Z was observed in Co-based amorphous wires, ribbons, and films.^{4), 8)–10)} The GMI effect due to the magnetization rotation is also possible in the case of a longitudinal magnetic structure (magnetization is parallel to the current and field direction), however, it is proving to have a much lower sensitivity and will not be discussed here.

The transverse domain structure is typical of Co-rich amorphous wires, ribbons and films and can be improved considerably during annealing under stress or magnetic field. Co-based amorphous alloys such as $(Co_{1-x}Fe_x)_{72.5}Si_{12.5}B_{15}$ possess a negative magnetostriction the value of which varies from -3×10^{-6} for $x=0$ to -10^{-7} for $x=0.06$. In the case of Co-rich amorphous wires the negative magnetostriction coupled with the compressive stress arising from quenching results in

Fig. 2 Magnetization orientation with respect to the external field, H_{ex} , anisotropy n_k , and circumferential direction e_ϕ

a circumferential anisotropy and a circular domain structure¹¹⁾ as in Fig. 1a.

2. Dynamic Magnetic Permeability

In the case of a transverse magnetic structure shown in Fig. 1, the magnetization caused by a current is composed of the domain wall motion and moment rotation. The corresponding magnetic permeability μ has two contributions:

$$\mu = 1 + 4\pi(\chi_{\text{dw}} + \chi_{\text{rot}}). \quad (1)$$

For high frequencies the domain wall motion is strongly damped by eddy currents. The parameter χ_{dw} is greatly reduced and can be considered in a linear approximation^{6), 7)}:

$$\chi_{\text{dw}} = \chi_{\text{dw}}^0 / (1 - j\omega/\omega_{\text{dw}}). \quad (2)$$

Here ω_{dw} is the relaxation frequency of domain wall motion, $1 + 4\pi\chi_{\text{dw}}^0$ is a linearized static permeability due to domain wall motion. This permeability decreases with the application of the field. As the frequency is increased and χ_{dw} drops, the rotational contribution of remagnetization grows and becomes dominant. An ac rotational susceptibility is a nondiagonal tensor ($\hat{\chi}_{\text{rot}}$). By using the standard procedure of the magnetic resonance theory,¹²⁾ the tensor $\hat{\chi}_{\text{rot}}$ can be found in the coordinate system with axis z along the equilibrium magnetization, M , as shown in Fig. 2. The vector M has to be previously defined by the energy minimization. We consider the case of a wire having in average the circumferential anisotropy. It is assumed that there is some dispersion of easy anisotropy axis, n_k , relative to the circular direction, e_ϕ . Then the non-zero components of $\hat{\chi}_{\text{rot}}$ are as follows:

$$\begin{aligned} \chi_{11} &= \Omega_M(\Omega_1 - j\alpha\omega)/D, \\ \chi_{22} &= \Omega_M(\Omega_H - j\alpha\omega)/D, \\ \chi_{12} &= -\chi_{21} = -j\omega\Omega_M/D, \\ D &= (\Omega_H - j\alpha\omega)(\Omega_1 - j\alpha\omega) - \omega^2, \\ \Omega_1 &= \gamma H_k(h \sin(\theta + \theta_k) + \cos 2\theta), \quad \Omega_M = \gamma M_s, \\ \Omega_H &= \gamma H_k(h \sin(\theta + \theta_k) + \cos^2 \theta). \end{aligned} \quad (3)$$

Here α is the spin relaxation parameter, γ is the gyromagnetic constant, θ_k is the angle between the local anisotropy axis n_k and e_ϕ , θ is the angle between M and

n_k , $h = H_{\text{ex}}/H_k$ is the reduced external field. The value of θ can be analytically determined only in the case of an ideal circumferential structure ($\theta_k = 0$), for which $\sin \theta = h$. Rotating the coordinate axes by angle $\theta + \theta_k$ we can write the tensor $\hat{\chi}$ in a cylindrical coordinate (e_r, e_ϕ, e_z).

When a current is flowing through a wire with a tensor permeability of form (3), the magnetic field has radial and circular components: $H = (H_r, H_\phi)$. Demanding $B_r = 0$, the relation between H_r, H_ϕ can be obtained

$$H_r = - \frac{4\pi\chi_{12} \sin(\theta + \theta_k)}{1 + 4\pi\chi_{11}} H_\phi.$$

Then the circular component of B can be written as

$$B_\phi = (1 + 4\pi(\chi_{\text{dw}} + \chi_{\text{rot}}))H_\phi = \mu_{\text{ef}}H_\phi,$$

where the effective permeability μ_{ef} is expressed as

$$\begin{aligned} \mu_{\text{ef}} &= 1 + 4\pi(\chi_{\text{dw}} + \sin^2(\theta + \theta_k)\chi_{\text{ef}}), \\ 4\pi\chi_{\text{ef}} &= 4\pi(\chi_{22} - 4\pi\chi_{12}^2/(1 + 4\pi\chi_{11})) \\ &= \frac{(\Omega_1 + 4\pi\Omega_M - j\alpha\omega)(\Omega_2 - j\alpha\omega) - \omega^2}{(\Omega_1 - j\alpha\omega)(\Omega_2 - j\alpha\omega) - \omega^2} - 1, \\ \Omega_2 &= \Omega_H + 4\pi\Omega_M. \end{aligned} \quad (4)$$

The parameter μ_{ef} defines the skin penetration depth in the case of the tensor magnetic permeability (3). In Fig. 3 the change in the field dependence of the effective permeability μ_{ef} with increasing frequency is shown. The value of μ_{ef} was averaged over the anisotropy axis n_k with the Gaussian distribution having dispersion $2\Delta\theta_k = 20^\circ$. It can be seen that the rotational processes dominate in high frequencies. The real part of μ_{ef} has a maximum, the position of which becomes closer to $h = 1$ with increasing frequency. Such permeability behavior results in a quite different field dependence of the impedance for relatively low frequencies $\omega < \omega_{\text{dw}}$ and high frequencies $\omega > \omega_{\text{dw}}$.

Note that the obtained result for the effective permeability is also valid in the case of a film with a uniaxial in-plane anisotropy.

3. Magneto-Impedance Spectra

Considering Maxwell's equations with the total permeability tensor, we deduce that the skin depth δ_m is defined by a standard way¹³⁾ by means of the effective permeability μ_{ef} (4)

$$\delta_m = c/\sqrt{2\pi\omega\sigma\mu_{\text{ef}}}, \quad (5)$$

where σ is the conductivity. Then, the expression for the impedance valid for a scalar case¹³⁾ can be used, since Z is defined by the total energy flux entering through the surface of a conductor. For a wire, the impedance has the form

$$Z = \frac{1}{2} R_{\text{dc}} ka \frac{J_0(ka)}{J_1(ka)}, \quad k = \frac{1+j}{\delta_m}. \quad (6)$$

Here R_{dc} is the resistance for a dc current, J_0, J_1 are Bessel functions, a is the wire radius. Using expressions (5) and (6) with the effective permeability defined by (4) we can calculate the impedance for any frequency.

Fig. 3 Effective magnetic permeability *versus* the external field for various frequencies: (a) real part and (b) imaginary part. From the B - H characteristic measurement for a cold-drawn and then tension-annealed amorphous wire, $4\pi M_s = 0.6 \times 10^4$ G and $H_k = 2.5$ Oe. For the domain wall permeability, the results given in refs. 6 and 7 are used. $\alpha = 0.1$.

Fig. 4 Field dependence of $|Z|/R_{dc}$ in a wire for various frequencies; $w = (a/\delta)^2$, $\delta = c/\sqrt{2\pi\omega\sigma}$: 1, 0.001; 2, 0.0025; 3, 0.004; 4, 0.0065.

Figure 4 shows the field dependence of the absolute value of impedance ($|Z|$) for various frequencies. For a relatively low frequency, $|Z|$ decreases quickly with increasing the field for $h < 1$ and it decreases little for $h > 1$. As the frequency is increased and the rotational mechanism is involved the character of impedance field dependence changes: $|Z|$ has a minimum at $h = 0$ and a maximum at $h \sim 1$, reflecting the field dependence of the effective permeability for different frequencies, shown in Fig. 3. In the case of a very strong skin effect ($a \gg \delta_m$), the relative change in impedance $\Delta Z/Z = 1 - |Z(H_{ex})/Z(0)|$ can be as much as 100% for $h \sim 1$.

Fig. 5 Voltage amplitude *versus* the external field for various current frequencies for 30- μ m-diameter tension-annealed wires. The annealing tension $\sigma_a = 2$ kg/mm². The theoretical curves are shown in dashed lines.

Fig. 6 Field dependencies of the impedance for as-cast and field-annealed films of 4 μ m thickness. The dashed curve corresponds to the theoretical values. From the B - H characteristics $4\pi M_s = 0.7 \times 10^4$ and $H_k = 10$ Oe. $\alpha = 0.3$.

A similar magnetic response of Z can be obtained for a film geometry as well. In this case the impedance is calculated as

$$Z = R_{dc} \cdot jka \coth(jka). \quad (7)$$

The model outlined above describes quite well the existing experimental data on GMI in amorphous wires and films.^{3), 4), 8)–10)} Figure 5 shows the field dependence of the voltage amplitude for various frequencies for a $\text{Co}_{68.2}\text{Fe}_{4.3}\text{Si}_{12.5}\text{B}_{15}$ amorphous wire having a small negative magnetostriction $\lambda \sim -10^{-7}$. A cold drawn down to 30 μ m in diameter and then tension annealed wire which has a well defined circumferential anisotropy is used. The voltage-field behavior is characteristically similar to that discussed above for the impedance.

With increasing frequency the maximum at a non zero field becomes more pronounced. For a comparison, the theoretical curves are also shown here in dashed lines.

As a film sample a CoFeB ($\lambda \sim -10^{-7}$) amorphous film of $4\mu\text{m}$ thickness obtained by sputtering is considered.¹⁰⁾ It has an in-plane uniaxial anisotropy which can be oriented along y -axis (see Fig. 1b) by transverse field-annealing. We can consider that the transverse magnetization M_y in the presence of H_{ex} (in z -direction) will be characterized by the same peculiarities as those discussed above for the case of the circular magnetization. However, the domain wall relaxation parameter for a stripe domain structure is larger than that for a circular one. For $d/a > 2$, where d is the domain spacing, the magnetic response of the impedance due to μ_{dw} (h) is not pronounced. Then a monotonic decrease in the voltage *versus* field may not be observed, as in Fig. 6 where the field dependencies of impedance for as cast and field annealed film samples are shown. The magnetic response is improved considerably by annealing which results in a perfectly transverse magnetic structure. Then the impedance sharply increases with the field for $H_{\text{ex}} < H_k$. The field at which the impedance has a maximum is nearly H_k . The theoretical curve is shown in dashed line. For calculation we use expressions (5) and (7) with the magnetic permeability $1 + 4\pi\chi_{\text{rot}}$ due to only the magnetization rotation.

4. Conclusion

In the high frequency case ($f \geq 10\text{ MHz}$ for a $30\mu\text{m}$ diameter amorphous wire) the magnetic response of impedance is associated with the field dependence of the ac rotational permeability, $\mu = 1 + 4\pi\chi_{\text{rot}}$. For the transverse magnetic structure with the magnetization perpendicular to the current and the external field, a considerable change in μ arises with magnetic fields of

the order of the anisotropy field. In this case the relative change in $Z(\Delta Z/Z = 1 - |Z(H_{\text{ex}})/Z(0)|)$ up to 100% is possible with $H_{\text{ex}} \cong H_k$, if the skin effect is sufficiently strong. There are some problems left to address, for example, we can predict that a very sensitive change in impedance has to occur in the ferromagnetic resonance region for any type of a magnetic structure.

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