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Simulation of stress-impedance effects in low magnetostrictive films

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Abstract

A theoretical study of stress-impedance effect based on the solution of Landau–Lifsitz–Gilbert equation has been carried out. The results show that stress impedance effects depend largely on several extrinsic (external bias field, external frequency) and intrinsic (orientation and magnitude of uniaxial anisotropy, damping) parameters.

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1. Introduction

Low magnetostrictive amorphous alloys have attractive magnetic properties in the high frequency range as high permeability, high saturation magnetic induction and low magnetic losses that make these materials suitable for observing the magneto-impedance (MI) and stress-impedance (SI) effects [1–5]. In recent years, stress-impedance effects based on magnetoelastic films showing the inverse magnetoelastic effect have been extensively studied because of scientific interests and industrial applications. As is well-known, the magneto-impedance (MI) effect is the variation of a.c. impedance of a ferromagnetic conductor in presence of an external field. The origin of MI is related to the behavior of the permeability, μ, at high frequency with the applied magnetic field [6,7] through the skin penetration depth, $\delta = \frac{c}{\sqrt{2\pi\sigma_c\omega\mu}}$ where σ_c and μ are the conductivity and permeability of the material, ω is the angular frequency and c is the speed of light. The permeability of a ferromagnetic conductor depends upon several factors, such as the external bias field, excitation frequency and current amplitude, external stress, magnetic anisotropy, heat treatment, etc. A tensile stress applied to a nearly zero magnetostrictive ribbon changes its saturation magnetostriction coefficient, due to the magnetoelastic interaction that is related to the strain dependence of the magnetic anisotropy energy [8]. This stress dependence of saturation magnetostriction coefficient together with the applied stress affects the effective anisotropy field and anisotropy of the ribbons. Hence a stress-impedance (SI) effect appears in the samples when a high frequency current generates the skin effect [9,10].

Most of the studies on magnetoelastic materials are experimental and there are relatively fewer theoretical studies as we know. In this paper, a skin effect based explanation of the SI phenomenon will be presented. Based on the skin effect explanation and the solution of Landau–Lifsitz–Gilbert equation, stress dependence of the impedance of a magnetoelastic film upon external magnetic field, external frequency, orientation of easy axis, magnitude of uniaxial anisotropy and damping parameters have been simulated.

2. Model and formulation

It is well known that the AC current is not homogenous over the cross-section of the magnetic conductor due to the

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screening of the e.m field. The screening is governed by the Maxwell equations along with the magnetization dynamics. In soft ferromagnetic materials, $\boldsymbol{M}$ becomes a non-linear function of $\boldsymbol{H}$ and this leads to nonlinear coupled equations for $\boldsymbol{M}$ and $\boldsymbol{H}$. Assuming a linear response of the material, the above coupled equation can be solved and the inhomogeneous distribution of the current is then characterized by the skin depth

$$\delta = \sqrt{\frac{1}{\sigma_c f \mu_0 \mu_{\text{eff}}}} \tag{1}$$

where 'f' is the frequency of the AC current, σ_c is the electrical conductivity and μ_{eff} is the effective permeability of the magnetic film. In magnetic films, the permeability μ_{eff} depends upon the frequency f, the amplitude of the bias magnetic field, the applied stress, etc. The impedance 'Z' of a long magnetic ribbon of thickness '2d' which has been excited by a current carrying signal coil of inductance 'L_0' wound across the ribbon is given by:

$$Z = -\mathrm{i}\omega L_0 \mu \tag{2}$$

where $\mu = \mu_{\text{eff}} \frac{\tanh(kd)}{kd}$ (3)

with $k = (1+\mathrm{i})/\delta$ (4)

and $L_0 = \frac{n^2 A_c}{2l}\mu_0$ is the inductance of the empty coil and μ_{eff} is the effective permeability.

The permeability μ_{eff} of the ferromagnetic material is a complex quantity due to magnetic relaxation and alters the impedance of the sample in a non-linear way in the presence of an external stress or magnetic field. As the permeability is a measure of magnetic response, it is necessary to consider the magnetization dynamics in the presence of a small excitation field and external parameters and then to estimate the permeability and its variation with these parameters. The magnetization dynamics of a ferromagnetic material on a macroscopic scale is customarily described by the Landau–Lifsitz–Gilbert equation:

$$\dot{\vec{\boldsymbol{M}}} = \gamma\left(\vec{\boldsymbol{M}} x \vec{\boldsymbol{H}}_{\text{eff}}\right) - \frac{\alpha}{M_s}\left(\vec{\boldsymbol{M}} x \dot{\vec{\boldsymbol{M}}}\right) - \frac{1}{\tau}\left(\vec{\boldsymbol{M}} - \vec{\boldsymbol{M}}_0\right) \tag{5}$$

Here $\boldsymbol{M}$ is the magnetization, γ is the gyromagnetic ratio, $\boldsymbol{M}_s$ the saturation magnetization, $\boldsymbol{H}_{\text{eff}}$ is the effective field and $\boldsymbol{M}_0$ the equilibrium magnetization. The first term on the right hand side of Eq. (5) is the torque acting on M due to $\boldsymbol{H}_{\text{eff}}$ and the second term is the Gilbert damping term with damping coefficient α. The last term is referred to as Bloch–Bloembergen damping with relaxation time τ. This does not preserve the magnitude of macroscopic magnetization, as is required for an ideal ferromagnet, and is used to describe the relaxation processes in materials with imperfect ferromagnetic order (such as amorphous and nanocrystalline alloys or crystals with some structural defects). It has been proved that the choice of the particular damping term substantially influences the imaginary part of effective permeability and consequently the magnitude of magneto-impedance effect [11]. The effective field $\boldsymbol{H}_{\text{eff}}$ can be written as:

$$\vec{\boldsymbol{H}}_{\text{eff}} = \vec{\boldsymbol{H}} + \vec{\boldsymbol{H}}_a + \vec{\boldsymbol{H}}_\sigma \tag{6}$$

where the exchange coupling field and the demagnetizing field have been neglected to simplify the computation. The corresponding fields are defined as follows: $\boldsymbol{H}$ is the sum of applied d.c. bias field and exciting a.c. field. The uniaxial anisotropy field, $\boldsymbol{H}_a$ is defined as:

$$\boldsymbol{H}_a = \frac{2\boldsymbol{K}_u}{\mu_0 \boldsymbol{M}_s^2}\vec{\boldsymbol{e}}_a\left(\vec{\boldsymbol{e}}_a \cdot \vec{\boldsymbol{M}}\right) = \frac{\boldsymbol{H}_k}{\boldsymbol{M}_s}\vec{\boldsymbol{e}}_a\left(\vec{\boldsymbol{e}}_a \cdot \vec{\boldsymbol{M}}\right) \tag{7}$$

where $\boldsymbol{e}_a$ is the unit vector along the easy axis. K_u is the uniaxial anisotropy constant and

$$H_k = \frac{2K_u}{\mu_0 M_s}$$

The applied stress effective field $\boldsymbol{H}_\sigma$ is:

$$\vec{\boldsymbol{H}}_\sigma = \frac{H_{\sigma 1}}{M_s}\vec{\boldsymbol{e}}_\sigma\left(\vec{\boldsymbol{e}}_\sigma \cdot \vec{\boldsymbol{M}}\right) \tag{8}$$

where $\boldsymbol{e}_\sigma$ is the unit vector along the applied stress direction and

$$H_{\sigma 1} = \frac{3\lambda\sigma}{\mu_0 M_s} \tag{9}$$

where λ is the magnetostriction coefficient. In presence of low amplitude driving current $\boldsymbol{I}$, the excitation a.c. field $\boldsymbol{h}$ is much smaller than the other magnetic fields. Therefore, the induced magnetization $\boldsymbol{m}$ is small and the deviation of $\boldsymbol{M}$ from its equilibrium orientation $\boldsymbol{M}_0$ is also small. So one can assume $\boldsymbol{H}_{\text{eff}} = H_{\text{eff0}} + h_{\text{eff}}$ and $\boldsymbol{M} = M_0 + m$ and the a.c. component of the vectors varies as

$$\boldsymbol{h}, \boldsymbol{h}_{\text{eff}}, m \alpha e^{\mathrm{i}\omega t} \tag{10}$$

where $\omega = 2\pi f$ is the circular frequency of the a.c. current.

From Eqs. 6, 7, 8 and (10) we get

$$H_{\text{eff0}} = \vec{\boldsymbol{H}} + \frac{H_k}{M_s}\vec{e}_a\left(\vec{e}_a \cdot \vec{M}_0\right) + \frac{H_{\sigma 1}}{M_s}\vec{e}_\sigma\left(\vec{e}_\sigma \cdot \vec{M}_0\right) \tag{11}$$

$$\begin{aligned} h_{\text{eff}} &= \vec{h} + \frac{H_k}{M_s}\vec{\boldsymbol{e}}_a(\vec{\boldsymbol{e}}_a \cdot \vec{\boldsymbol{m}}) + \frac{H_{\sigma 1}}{M_s}\vec{e}_\sigma(\vec{e}_\sigma \cdot \vec{\boldsymbol{m}}) \\ &= \vec{\boldsymbol{h}} + \vec{\boldsymbol{h}}_a \end{aligned} \tag{12}$$

Substituting Eqs. (10)–(12) into (5) and then rewriting (5)

$$\frac{\mathrm{i}\omega^*}{\gamma}\vec{\boldsymbol{m}} + \left(\frac{\mathrm{i}\alpha\omega}{\gamma}\frac{\vec{\boldsymbol{M}}_0}{\vec{\boldsymbol{M}}_s} + \vec{\boldsymbol{H}}_{\text{eff0}}\right) \times \vec{\boldsymbol{m}} = \left(\vec{\boldsymbol{M}}_0 \times \vec{\boldsymbol{h}}_{\text{eff}}\right) \tag{13}$$

Here $\omega^* = \omega - \mathrm{i}/\tau$, where τ is related to the relaxation frequency, ω_0, by $\omega_0 = 1/\tau$.

The magnetic ribbon is modeled as a system with a uniform uniaxial in-plane magnetic anisotropy oriented at an angle θ_0 with respect to the z-axis (Fig. 1).

The stress σ or d.c. field ($\boldsymbol{H}$) is assumed to be applied along the z-axis and the magnetization $\boldsymbol{M}_0$, in the absence of a.c. field, lies in the film plane at an angle θ with respect to the z-axis. The a.c. components of magnetization can be