Modeling of magnetoimpedance effect in nanostructured multilayered films

N A Buznikov1 and G V Kurlyandskaya2

1 Scientific and Research Institute of Natural Gases and Gas Technologies – Gazprom VNII GAZ, 142717 Razvilka, Leninsky District, Moscow Region, Russia
2 Department of Magnetism and Magnetic Nanomaterials, Institute of Natural Sciences and Mathematics, Ural Federal University, Ekaterinburg 620002, Russia

E-mail: n_buznikov@mail.ru

Abstract. The magnetoimpedance effect in nanostructured multilayers is studied theoretically. The multi-layered film structure consists of highly conductive non-magnetic central layer and two external multilayers containing soft magnetic layers of the same thickness separated either by magnetic spacers of different kind or by non-magnetic spacers. In order to describe the magnetoimpedance in the multilayer an electrodynamic model is proposed. The influence of geometric parameters and physical properties of the layers on the magnetoimpedance response is analyzed. The results obtained could be useful both for better understanding of high-frequency behavior of nanostructured multilayers and for optimization of multilayer parameters aiming to enhance the magnetoimpedance effect for practical applications.

1. Introduction

The magnetoimpedance (MI) effect consists in the change of the total impedance of a ferromagnetic conductor in the presence of an external magnetic field. The interest in the MI is related to the possibility of its application for the development of magnetic-field sensors, including magnetic biodetectors [1–3]. From the point of view of the miniaturization, permalloy based thin-film structures with the total thickness of magnetic layers of the order of microns are one of the most attractive materials for MI sensitive elements. Magnetic properties of permalloy films depend on their thickness due to the transition into a “transcritical state” [4]. Thick permalloy film is characterized by the appearance of an out-of-plane magnetic anisotropy component, high coercivity and low MI [5,6]. The thickness corresponding to the transition into a “transcritical state” depends on many parameters and can vary in the range from a few nanometers to a few hundred nanometers [6].

In order to solve the problem of the “transcritical state” transition and to increase the total film thickness, nanostructured multilayers have been proposed [7]. In these structures, the permalloy layers are separated by thin non-magnetic spacers. The MI effect was studied experimentally for multilayered structures, when different materials (e.g., Cu, Ag and Ti) were used as the spacers [7–12]. The magnetic properties and MI effect were also investigated for multilayers having magnetic spacers of different kind [13]. It was found that an appropriate choice of the magnetic spacer material and thickness allows one to improve the softness of the permalloy based nanostructured multilayers and their MI response. The experimental data concerning the influence of the material and thickness of the spacers on the MI behavior in multilayered structures are very limited, and further systematic investigation is required including a theoretical study. Recently, a model to describe the MI in nanostructured multi-
layers was proposed and tested [14]. The MI response was found by means of a simultaneous solution of linearized Maxwell equations and the Landau–Lifshitz equation for the magnetization motion.

In this work, we use the approach developed in [14] for analysis of the MI in nanostructured multilayered films with different geometric parameters and materials of both the non-magnetic and magnetic spacers.

2. Model
The studied [F/X]_n/F/C/[F/X]_m/F multilayered structure consists of highly conductive non-magnetic central layer C of a thickness 2d, and two external multilayers (see figure 1). The external multilayers contain permalloy layers F separated either by the magnetic or non-magnetic spacers X. The thickness of the spacers is d, and the thickness of the permalloy layers is d_2. The corresponding conductivities of the layers C, X and F are σ_0, σ_1, and σ_2. The multilayer length and width are l and w, respectively.

The alternating driving voltage \( U = U_{dr} \exp(-i\omega t) \) is applied to the multilayered structure, and the external magnetic field \( H_e \) is parallel to its long side. Since the multilayer element length and width are much higher than its thickness, we assume that electromagnetic fields depend only on the coordinate perpendicular to the film plane (x-coordinate). Taking into account the symmetry, we consider further the region of \( x > 0 \) only.

In the one-dimensional approximation, solution of Maxwell equations for the amplitudes of the longitudinal electric field \( e_j \) and the transverse magnetic field \( h_j \) in the layers can be presented in the following form:

\[
e_j = (e \pi k / 4 \pi \sigma_k) [A_j \cosh(p_k x) + B_j \sinh(p_k x)]
\]

\[
h_j = A_j \sinh(p_k x) + B_j \cosh(p_k x)
\]

Here \( j = 0, \ldots, 2n + 1 \) is the layer number; \( k = 0, 1 \) and 2 corresponds to central layer, spacer and permalloy layer, respectively; \( A_j \) and \( B_j \) are the constants; \( p_k = (1 - i) / \delta_k; \delta_k = c / (2 \pi \sigma k \mu_k)^{1/2}; c \) is the speed of light in vacuum; \( \sigma_k \) and \( \mu_k \) are the conductivity and the transverse permeability of the layer \( k \), respectively. For the central layer \( (j = k = 0) \) we have \( \mu_0 = 1 \). Due to the symmetry, the constant \( B_0 \) is equal to zero.

To describe the field distribution outside the multilayer we use the approximate solution for the vector potential obtained previously [15]. The field amplitudes \( e_{ext} \) and \( h_{ext} \) in the external region can be written as follows

\[
e_{ext} = C \frac{i \omega l}{2e c w} \left[ \frac{l}{w} \ln \left( \frac{R + w}{R - w} \right) - \frac{4x}{l} \arctan \left( \frac{wl}{2Rx} \right) \right]
\]

\[
h_{ext} = C (2/w) \arctan (iwl / 2Rx)
\]

Here \( C \) is the constant and \( R = (l^2 + w^2 + 4x^2)^{1/2} \). Note that equations (3) and (4) are valid if the multilayer width is much higher than its thickness: \( w >> 2d \), where \( d = d_0 + n d_1 + (n + 1) d_2 \).

To find the constants \( A_j \), \( B_j \) and \( C \) in equations (1)–(4), we should take into account the continuity conditions for the fields at the interfaces between the layers. Additional restrictions for the field amplitudes at the surface of the multilayer \( x = d \) follow from the conditions of the multilayer excitation by the driving voltage with the amplitude \( U_{dr} \):

\[
e_{2n+1}(d) = e_{ext}(d) + U_{dr} / l
\]

\[
h_{2n+1}(d) = h_{ext}(d)
\]
When the field distribution is obtained, we can found the impedance $Z$ of the multilayered structure as a ratio of the applied driving voltage to the total current $I$ flowing through the multilayer:

$$Z = \frac{U_{dr}}{I} = \frac{(2\pi/cw) \times U_{dr}}{h_{ex}}$$

(7)

The MI response of the multilayered structure is controlled by the transverse permeability in the permalloy layers. We assume that the value of the permeability is governed by the magnetization rotation only. This approximation is known to be valid at relatively high frequencies, when the domain-wall motion is strongly damped [16]. It is assumed that all permalloy layers possess the same physical properties and have an uniaxial in-plane magnetic anisotropy. The distribution of the magnetization in the permalloy layers can be found by minimizing the free energy. The minimization procedure results in the following equation for the magnetization equilibrium angle $\theta$ in the permalloy layers:

$$H_a \sin(\theta - \psi) \cos(\theta - \psi) = H_e \cos \theta$$

(8)

where $\psi$ is the anisotropy axis angle with respect to the transverse direction and $H_a$ is the anisotropy field.

The transverse permeability in the permalloy layers can be found by means of the solution of the linearized Landau–Lifshitz equation. The transverse permeability $\mu_2$ is given by [17]

$$\mu_2 = 1 + \frac{\gamma 4\pi M (\gamma 4\pi M + \omega_1 - i\kappa \omega) \sin^2 \theta}{(\gamma 4\pi M + \omega_1 - i\kappa \omega)(\omega_2 - i\kappa \omega)}$$

(9)

Here $M$ is the saturation magnetization, $\gamma$ is the gyromagnetic constant, $\kappa$ is the Gilbert damping parameter, $\theta$ is given by equation (8) and

$$\omega_1 = \gamma[H_a \cos^2(\theta - \psi) + H_e \sin \theta]$$

$$\omega_2 = \gamma[H_a \cos(2(\theta - \psi)) + H_e \sin \theta]$$

(10)

For further analysis, to describe a relative variation of the multilayer impedance with the external field we introduce the MI ratio $\Delta Z/Z$, which is given by

$$\Delta Z/Z \% = 100 \times \frac{Z(H_e) - Z(H_0)}{Z(H_0)}$$

(11)

where $H_0 = 100$ Oe is the value of the external field sufficient to reach a magnetic saturation state.

To analyze the frequency dependence of the MI response we use the maximum MI ratio $(\Delta Z/Z)_{max}$, which is defined as follows

$$(\Delta Z/Z)_{max} \% = 100 \times \frac{Z_{max} - Z(H_0)}{Z(H_0)}$$

(12)

where $Z_{max}$ corresponds to the peak value in the field dependence of the MI ratio at given frequency.
3. Results and discussion

The developed model allows one to analyze the influence of the multilayer parameters on the field and frequency dependences of the MI response. Figure 2 shows the field dependence of the MI ratio for the multilayered structure calculated at different frequencies for the case when the central layer and spacers are made of the same material ($\sigma_0 = \sigma_1$). The results are presented only for the region of the positive fields, since the calculated field dependences of the MI are symmetrical with respect to the sign of the external magnetic field in the framework of the model. The dependence of the MI ratio on the external field shows a typical behavior with a peak near the anisotropy field $H_a$. For the studied multilayer, the maximum values of the MI ratio are achieved within the frequency range from 50 to 100 MHz (see figure 2).

Figure 2. MI ratio as a function of the external field at different frequencies $f = \omega / 2 \pi$. Parameters used for calculations are $l = 1$ cm, $w = 0.02$ cm, $2d_0 = 500$ nm, $d_1 = 3$ nm, $d_2 = 50$ nm, $n = 9$, $M = 750$ G, $H_a = 10$ Oe, $\sigma_0 = \sigma_1 = 5 \times 10^{17}$ s$^{-1}$, $\sigma_2 = 3 \times 10^{16}$ s$^{-1}$, $\gamma = 0.05 \pi$ and $\kappa = 0.02$.

Figure 3 illustrates the influence of the thickness of the central layer on the frequency dependence of the maximum MI ratio calculated by means of equation (12). The value of $(\Delta Z / Z)_{\text{max}}$ increases with the thickness of the central layer, and the maximum MI is reached at lower frequencies with a growth of $2d_0$. Note that the calculated results are in a qualitative agreement with the experimental data for FeNi/Cu multilayers [18] and results of simulation by means of Finite Element Method [11].

Figure 4 presents the frequency dependence of $(\Delta Z / Z)_{\text{max}}$ calculated for multilayered films with different values of the central layer conductivity $\sigma_0$. It follows from figure 4 that the MI effect is relatively small when the central layer conductivity is of the order of the permalloy one. The peak in the frequency dependence of the maximum MI ratio increases significantly and shifts towards lower frequencies with a growth of $\sigma_0$. Similar results have been obtained previously in the modeling of the MI response for three-layered films [19]. Therefore, the use of the material with high conductivity (e.g., Cu or Ag) is preferable in order to achieve high values of the MI response in multilayers.

Figure 5 shows the frequency dependence of $(\Delta Z / Z)_{\text{max}}$ at different values of the thickness $d_1$ of separating layers. It follows from figure 5 that the MI ratio increases with a decrease of $d_1$, since an
increase of the thickness of the separating layer leads to a growth of the resistance of the multilayer and to the corresponding decrease of the MI ratio.

Figure 4. Frequency dependence of maximum MI ratio at different values of the central non-magnetic layer conductivity $\sigma_0$. Curve 1, $\sigma_0 = 10^{16}$ s$^{-1}$; 2, $\sigma_0 = 5 \times 10^{16}$ s$^{-1}$; 3, $\sigma_0 = 10^{17}$ s$^{-1}$; 4, $\sigma_0 = 2 \times 10^{17}$ s$^{-1}$; 5, $\sigma_0 = 5 \times 10^{17}$ s$^{-1}$. Other parameters used for calculations are the same as in figure 2.

Figure 5. Frequency dependence of maximum MI ratio at different values of the thickness $d_1$ of spacers. Other parameters used for calculations are the same as in figure 2.

Note that at very low values of $d_1$, the exchange interactions between permalloy layers appear, and this fact can affect essentially the MI response. The critical thickness of the separating layer is of the order of several nanometers and depends significantly on the properties of magnetic layers.

Several experimental studies of the MI effect have been carried out for multilayers with the copper central layer and titanium spacers [11,12]. The influence of the difference in the conductivities of the central layer and spacers on the frequency dependence of the maximum MI ratio is presented in figure 6. The value of $(\Delta Z/Z)_{\text{max}}$ increases with a decrease of the conductivity $\sigma_1$ of the separating layers, and the maximum MI ratio changes slightly when $\sigma_1$ becomes of the order of the permalloy conductivity $\sigma_2$. Thus, the use of the spacers with lower conductivity allows one to enhance the MI effect in multilayers.

Let us analyze the MI response in multilayered films with magnetic spacers, i.e. for the case of permeability $\mu_1 \neq 1$. High permeability of the spacers causes the changes in the distribution of electromagnetic fields within the multilayered structure and affects the MI response. To describe qualitatively the influence of the magnetic spacers on the MI, we assume that the permeability of the spacers $\mu_1 = \mu_{\text{sp}}$ at $H_e = 0$ and decreases gradually to $\mu_1 = 0.1 \mu_{\text{sp}}$ at $H_e = H_0 = 100$ Oe. It is also assumed for simplicity that the value of $\mu_1$ is independent of the frequency.

Figure 7 shows the frequency dependence of $(\Delta Z/Z)_{\text{max}}$ calculated for multilayers with magnetic and non-magnetic spacers for two values of the spacer conductivity $\sigma_1$ and $\mu_{\text{sp}} = 2000$ for the magnetic spacers. As follows from figure 7, for multilayers with magnetic spacers the maximum MI ratio slightly increases in comparison with the multilayers having non-magnetic spacers. The increase of $(\Delta Z/Z)_{\text{max}}$ in the multilayers with magnetic spacers can be explained as follows. In the case of magnetic spacers, the difference between the skin depths in the spacers $\delta_1$ and in the permalloy layers $\delta_2$...
becomes less pronounced. Correspondingly, the field distribution within the external multilayers has higher uniformity, that leads to the increase of the MI effect.

**Figure 6.** Frequency dependence of maximum MI ratio at different values of the conductivity \( \sigma_1 \) of spacers. Curve 1, \( \sigma_1 = 5 \times 10^{17} \text{ s}^{-1} \); 2, \( \sigma_1 = 2 \times 10^{17} \text{ s}^{-1} \); 3, \( \sigma_1 = 10^{17} \text{ s}^{-1} \); 4, \( \sigma_1 = 5 \times 10^{16} \text{ s}^{-1} \); 5, \( \sigma_1 = 10^{16} \text{ s}^{-1} \). Other parameters used for calculations are the same as in figure 2.

**Figure 7.** Frequency dependence of maximum MI ratio for multilayers with non-magnetic (solid lines) and magnetic spacers (dashed lines), \( \mu_{sp} = 2000 \). Curves 1 and 2, \( \sigma_1 = 2 \times 10^{17} \text{ s}^{-1} \); 3 and 4, \( \sigma_1 = 5 \times 10^{16} \text{ s}^{-1} \). Other parameters used for calculations are the same as in figure 2.

The results of modeling allow one to explain qualitatively main features of the field and frequency dependences of the MI response in nanostructured multilayers observed in experimental studies. Some disagreements between the calculated results and experimental data may be attributed to approximations of the model. In particular, the hysteresis and asymmetry were observed in the field dependences of the MI in different multilayers. One of the possible reasons of the asymmetry may be related to magnetostatic coupling between magnetic layers [20].

Such coupling is neglected in the model proposed. In order to understand the influence of the magnetostatic interactions on the MI response in multilayered films, a more systematic investigation is required. In the framework of the model, the magnetostatic interactions can be taken into account qualitatively by introducing effective bias field acting on some permalloy layers.

In conclusion of this section, note that it has been demonstrated that the MI in nanostructured multilayered films could be promising for the development of magnetic biosensors [3,21]. In a magnetic biosensor, non-uniform magnetic fields having a complex configuration should be analyzed. In this connection, recently non-symmetric nanostructured multilayered films obtained by the deposition of top and bottom ferromagnetic parts of a multilayer with different thicknesses have attracted considerable attention [22]. The approach presented in this work could be also used for theoretical analysis of the MI effect in non-symmetric nanostructured multilayers [14].

**4. Conclusions**

We study theoretically the MI effect in nanostructured multilayered films consisting of highly conductive non-magnetic central layer and two external multilayers containing permalloy layers separated by non-magnetic or magnetic spacers. The distribution of the electromagnetic fields within the multilayer and the impedance are obtained by means of a solution of linealized Maxwell equations together with the Landau–Lifshitz equation for the magnetization motion. The model proposed allows one to
analyze the influence of multilayer parameters on the MI response. The results of modeling are in a qualitative agreement with experimental data obtained previously for different multilayered films. It is shown that a growth of the thickness of separating non-magnetic spacers results in a decrease of the MI ratio, and the MI increases when the conductivity of the spacers decreases and becomes comparable in magnitude with the permalloy conductivity. In addition, it is demonstrated that the use of the magnetic spacers may lead to the further increase of the MI ratio. The approach developed could be used for analysis of experimental studies of the MI in multilayers and for optimization of MI sensitive element parameters.

Acknowledgment
This research was funded by the Russian Science Foundation, grant number 18-19-00090.

References
[1] Uchiyama T, Mohri K, Honkura Y and Panina L V 2012 IEEE Trans. Magn. 48 3833
[2] Semirov A V, Moiseev A A, Bukreev D A, Kovaleva N P, Vasyukhno N V and Nemirova V A 2017 Phys. Met. Metallogr. 118 535
[3] Wang T, Zhou Y, Lei Ch, Luo J, Xie Sh and Pu H 2017 Biosens. Bioelectron. 90 418
[4] Sugita Y, Fujiwara H and Sato T 1967 Appl. Phys. Lett. 10 229
[5] Svalov A V, Kurlyandskaya G V, Hammer H, Savin P A and Tutynina O I 2004 Tech. Phys. 49 868
[6] Svalov A V, Asequinolaza I R, García-Arribas A, Orue I, Barandiaran J M, Alonso J, Fernández-Gubieda M L and Kurlyandskaya G V 2010 IEEE Trans. Magn. 46 333
[7] Kurlyandskaya G V, Elbaile L, Alves F, Ahamada B, Barraú R, Svalov A V and Vas’kovskiy V O 2004 J. Phys.: Condens. Matter 16 6561
[8] Correa M A, Bohn F, Chesman C, da Silva R B, Viegas A D C and Sommer R L 2010 J. Phys. D: Appl. Phys. 43 295004
[9] Kurlyandskaya G V, Svalov A V, Fernández E, García-Arribas A and Barandiarán J M 2010 J. Appl. Phys. 107 09C502
[10] Kurlyandskaya G V, García-Arribas A, Fernández E and Svalov A V 2012 IEEE Trans. Magn. 48 1375
[11] García-Arribas A, Fernández E, Svalov A, Kurlyandskaya G V and Barandiarán J M 2016 J. Magn. Magn. Mater. 400 321
[12] García-Arribas A, Combarro L, Goriena-Goikoetxea M, Kurlyandskaya G V, Svalov A V, Fernández E, Orue I and Feuchtwanger J 2017 IEEE Trans. Magn. 53 2000605
[13] Svalov A V, Fernandez E, Garcia-Arribas A, Alonso J, Fdez-Gubieda M L and Kurlyandskaya G V 2012 Appl. Phys. Lett. 100 162410
[14] Buznikov N A and Kurlyandskaya G V 2019 Sensors 19 1761
[15] Sukstanskii A, Korenivski V and Gromov A 2001 J. Appl. Phys. 89 775
[16] Kraus L 1999 J. Magn. Magn. Mater. 196-197 354
[17] Panina L V, Mohri K, Ushiyama T, Noda M and Bushida K 1995 IEEE Trans. Magn. 31 1249
[18] Volchkov S O, Fernández E, García-Arribas A, Barandiaran J M, Lepalovskiy V N and Kurlyandskaya G V 2011 IEEE Trans. Magn. 47 3328
[19] Panina L V and Mohri K 2000 Sens. Actuators A 81 71
[20] Vas’kovskiy V O, Savin P A, Lepalovskii V N and Ryazantsev A A 1997 Phys. Solid State 39 1958
[21] Kurlyandskaya G V, Fernandez E, Safronov A P, Svalov A V, Beketov I, Burgoa Beitia A, García-Arribas A and Blyakhman F A 2015 Appl. Phys. Lett. 106 193702
[22] Kurlyandskaya G V, Chlenova A A, Fernández E and Lodewijk K J 2015 J. Magn. Magn. Mater. 383 220