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Modeling of Magnetic Field Influence on Electrophysical Effects in Magnetoimpedance Microwires

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The pursuance of the research of dependency between magnetoimpedance effect and the distribution of magnetization relatively to amorphous ferromagnetic microwire axis is important for creating high-sensitive magnetic field sensors. Distribution of signal in skin-layer is considered as a function of the magnetic properties of the wire material, bias current flowing through it, strength and orientation of the external magnetic field. The impact of these factors on the signal of microwire with circumferential (helical) anisotropy is analyzed on the base of numerical simulation.

Keywords: Magnetization, Circumferential (helical) magnetic anisotropy, Magnetoimpedance sensor, Amorphous magnetic microwire, Bias current, Bias field.

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1. INTRODUCTION

Nowadays, in the microsystem technology the issue of creating of high-sensitive sensors for weak magnetic fields and currents is actual [1]. Sensors based on magnetoimpedance effect (MI) has possibility to measure magnetic fields in the range of widely known magnetoresitive sensors and even SQUID sensors [2, 3]. The MI effect is most strongly manifested in cylindrical amorphous wires in which the circumferential(helical) magnetic anisotropy of a specific structure is formed for high output signal values in the top layer with longitudinal orientation of magnetization vector $\boldsymbol{M}$. Microwires with core of soft magnetic amorphous materials is commonly used as magnetic sensitive elements. Diameter of wires is 10-50 μm and glass shell thickness is 2-3 μm. Amorphous material of conducting body has very narrow B/H loop and its typical parameters are: magnetization intensity M_s ~ 100...500 G, effective field of circular anisotropy in quasistatic reversal magnetization or in low frequency magnetic field $H_K = 1$ ... 5 Oe, permeability measured on 10 kHz frequency in non-satured sample is 10^4.

It is assumed that during the flow of AC the magnetodynamics of such system is due to small oscillations of the magnetization vector $\boldsymbol{M}$ with respect to its stationary position. External magnetic field $\boldsymbol{H}$ applied along the axis of the conductor changes the orientation of the magnetization in the outer microwire layer, its effective permeability μ_{ef} and inductance. Therefore, the values of the effective magnetic permeability and thickness of the skin layer enter in the relations between the magnitude of the MI element signal, external conditions and characteristics of the wire material [4]:

$$V_c = R_0\left(\pi n a\right)\frac{a}{2\delta_0}\left[\left(\sqrt{\mu_{ef}}-1\right)\sin 2\psi\right]i \qquad (1)$$

Here, n represents number of turns per unit length of the detection coil, ψ is the angle between the magnetization vector $\boldsymbol{M}$ and the axis of the wire, i is the amplitude of the excitation current, δ_0 is skin thickness at $\mu_{ef} = 1$ defined by the expression:

$$\delta_0 = c[\rho/(2\pi\omega)]^{1/2}, \qquad (2)$$

where c is the speed of light, ω is circular frequency of the alternating current, ρ is specific electrical resistivity of the material of the ferromagnetic conductor.

Thus, the surface impedance depends on both the dynamic permeability and on static component of the orientation of magnetization which may have especially high sensitivity to external conditions.

Domain structure complicates the picture of the magnetization distribution in the wire. Therefore, it are usually suppressed by the magnetic bias field H_b generated by the DC component of the excitation current which magnetizes the wire in a circular direction.

2. DISTRIBUTION OF MAGNETIZATION IN SKIN-LAYER MI-MICROWIRE UNDER THE INFLUENCE OF EXTERNAL MAGNETIC FIELDS

The influence of the external magnetic field on the signal of the sensor element was studied experimentally in [5, 6] and the problem of the magnetization distribution under the influence of external field was solved in [7].

The equilibrium orientation of magnetization vector $\boldsymbol{M}$ in microwire with circular magnetic anisotropy depending on materials properties, external magnetic field $\boldsymbol{H}$ (with components along axis of wire H_z and perpendicularly to ot H_y) and magnetic bias field H_b. On the Fig. 1 this direction is represented as polar angle ψ and azimuth angle φ, angle θ is showing deviation of vector of external field $\boldsymbol{H}$ from conducting body axis z to axis y (Fig. 1).

The analysis of system energy gives this equation:

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$$\pm(H_b + H_y cos\varphi) - H_z tg\psi + [1-(4\pi M / H_k)\times \times(H_y sin\varphi)^2 / (H_b \pm 4\pi M sin\psi)^2] H_k \sin\psi = 0, \quad (3)$$

where low sign is going with clause

$$Arccos(-H_b / H_y) < \varphi < 360^{\circ} - Arccos(-H_b / H_y)$$

The formula (3) allows to define an orientation of magnetization vector ***M*** in every point on the microwire surface, which is characterized with azimuth angle φ.

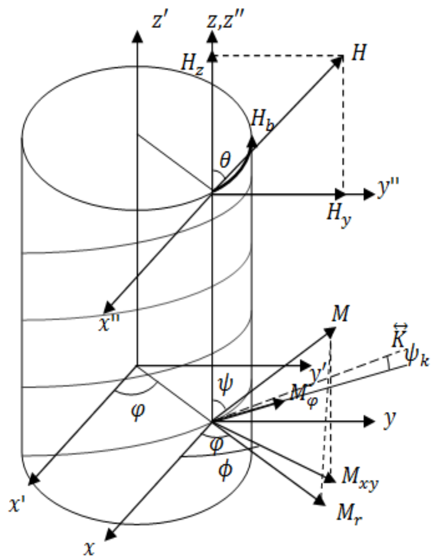

Fig. 1 – Geometry and main features of the MI element

For numerical simulation of equation (3) relatively to deviation angle of magnetization vector ***M*** from microwire axis for various azimuth angle φ, we were used following typical values of system properties, specific for usual on practice conditions: strength of the external magnetic field H_y, H_z (to 10 Oe), magnetic bias field H_b (to 6 Oe), anisotropy field H_k = 1-5 Oe, $4\pi M$ = 500 G.

For calculation it was used C++ programming environment to implement algorithm for transcendental equations solution by using bisection method, where the finding roots of equation in certain interval of values was applied. Therefore, it is necessary to analyze system behavior in different external conditions. Furthermore, so far as the sign + or – of formula (3) defines by position of φ angle in critical regions Fig. 2, it is possible to get more than one root in one iteration. To choose right interval with desired solution conditions, where azimuth angle φ was 0°, 90°, 180°, 270° and at $\varphi = \varphi_{critical}$ were considered.

The correct choice of initial conditions in numerical simulation could be defined by using simplified schedule of dependence between magnetization vector ***M*** in skin-layer (on the surface of microwire) and azimuth angle $\cos(\psi) = f(\varphi)$, which is shown in Figs. 3, 4. Plot in Fig. 4 is not accurate, because real dependence doesn't have sharp angles. There are shown only specific and critical angles. Using the data from this curve it is possible to exclude situation when initial interval of iteration process has excess roots. If the curve increases in some section on the horizontal axis next root of equation (3), which is located на the vertical axis, must be larger than previous one. In the opposite situation next root should be lesser than previous. On this basis, calculation of angle ψ for any values of azimuth angle φ excludes finding of wrong solutions of the problem in critical and significant regions.

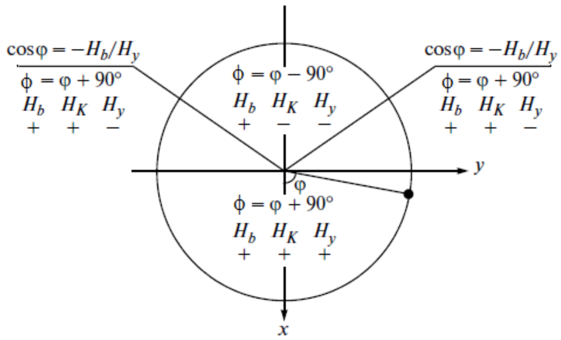

Fig. 2 – Critical regions with change of sign in expression (3) and significant solution regions of system

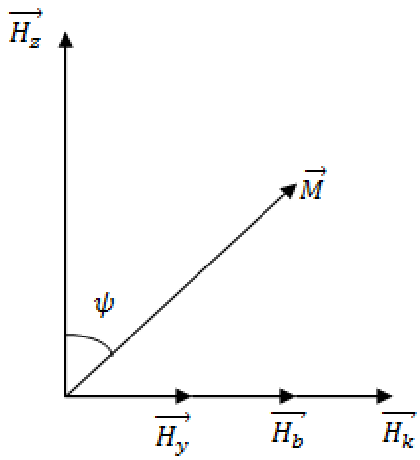

Fig. 3 – Simplified schedule of subtask for initial location discovery of bisection method

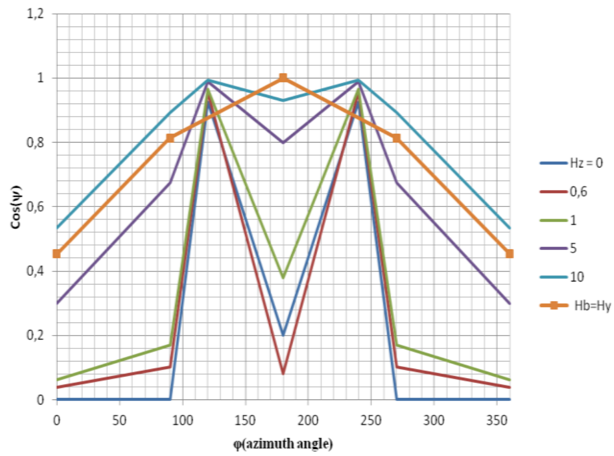

Fig. 4 – Dependence of longitudinal component of magnetization (axial) from location on microwire surface (azimuth angle)

3. DISTRIBUTION OF MICROWIRE SIGNAL IN DEPENDENCE ON EXTERNAL EXCITATION CONDITIONS

As can be seen from (1), the value of microwire signal depends both on magnetization vector $\boldsymbol{M}$ orientation and on effective permeability. By using previously obtained model of distribution of magnetization in microwire it is possible to simulate distribution of signal magnetization of magnetoimpedance sensor element, which could be represented as average value of function $\sin(2\psi) = f(H_z)$ on the wire surface. This statement is justify if we assume that current density in skin-layer of MI-element signal is homogeneous and the registration of signal is inductive with using coils. Distribution could be simulated by numerical integration if surface of a wire will be divided in N regions, which affects on the general magnetization of the system separately. In this paper it was suggested to divide microwire on 360 intervals in cross-section and find solution in the region of azimuth angle $\varphi \in [0; 360]$ with 1° pitch.

The value of effective permeability, which depends on frequency of excitation, may be found as [4]:

$$\mu_{ef} = 1 + 4\pi\chi \approx 4\pi\chi, \qquad (8)$$

where χ is magnetic susceptibility of ferromagnetic core of microwire.

Magnetic susceptibility is defined from equation:

$$\chi = \frac{\omega_M(\omega_2 - j\tau\omega) + 4\pi\omega_M^2}{(\omega_1 - j\tau\omega)(\omega_2 + 4\pi\omega_M - j\tau\omega) - \omega^2} \qquad (9)$$

where

$$\begin{cases} \omega_1 = \gamma[H_{ex}\cos\psi + H_b\sin\psi + H_K\cos 2\psi], \\ \omega_2 = \gamma[H_{ex}\cos\psi + H_b\sin\psi + H_K\cos^2\psi], \\ \quad H_K = 2K/M_s,\ \omega_M = \gamma M_s,\ j = \sqrt{-1}, \end{cases} \qquad (10)$$

gyromagnetic ratio γ and the parameter of relaxation τ are taken to be equal to $1{,}76\cdot10^7$ $s^{-1}Oe^{-1}$ and 0,2 relatively.

Considering how values of the expression (9) are correlated between themselves we can simplify formulas (9) and (10) to use it in calculation. In our case $M_s = 500$ G, $f = 8$ or 20 MHz. Values of ω_1 and ω_2 were calculated for the following parameters: $H_b = 5$ Oe, $H_y = 10$ Oe, $H_k = 1$ Oe. For another correlations of H_b and H_y this values have the same order of magnitude. The data of this analysis is represented on the Table 1.

Based on estimation of the quantities in the formula (9) for typical values of the circular frequency of the current ω and relaxation parameter τ and based on the dependence of ω_1 and ω_2 on the longitudinal component of external magnetic field H_z (Fig. 6) we get the typical values of parameters collected in Table 1. Thus, $\omega_1 \approx \omega_2$, $4\pi\omega_M^2 >> \omega\tau\omega_M$ and $\omega\tau >> \omega^2/4\pi\omega_M$ in 1-2,5 order of magnitude, and (9) could be rewrited as

$$\chi = (4\pi\omega_M^2)/(4\pi\omega_M(\omega_1 - j\tau\omega) - \omega^2), \qquad (11)$$

or

$$\chi = \omega_M/((\omega_1 - j\omega\tau - \omega^2/(4\pi\omega_M)) \qquad (12)$$

The last summand in denominator could be discarded, so we get:

$$\chi = \omega_M/(\omega_1 - j\omega\tau) \qquad (13)$$

By multiplying on complex conjugate of numerator we get:

$$\chi = \omega_M(\omega_1 + j\omega\tau)/(\omega_1^2 + \omega^2\tau^2) \qquad (14)$$

The absolute value of susceptibility is

$$|\chi| = \omega_M/\sqrt{\omega_1^2 + \omega^2\tau^2}\ . \qquad (15)$$

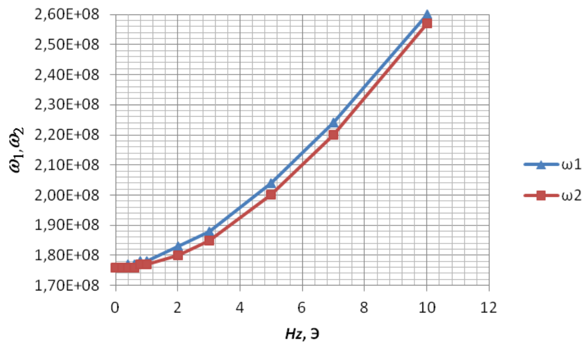

Fig. 6 – Dependence of ω_1 and ω_2 included in the equation (9) on longitudinal component of external field H_z with constant value of $H_b = 5$ Oe, $H_y = 10$ Oe, $H_k = 1$ Oe

From expressions (1), (8) and (15) it is possible to calculate the signal of wire for different values of parameters of system (Fig. 7). The most pronounced linear part is related to curve, where correlation between magnetic bias field H_b and the transverse component of the external field H_y is equal to 1. The most strong absolute value signal could be shown when the transverse component of the external field H_y. is equal to 0.

In previous article [7] the problem of magnetization distribution was solved for circular magnetic anisotropy. In the case of helical anisotropy the direction of easy magnetization in any point of skin-layer is determined by tangent to the helix on the surface of the microwire. The level of helical angle ψ_K is given by angle between tangent and sectional plane of the wire.

The equilibrium magnetization vector $\boldsymbol{M}$ angle deflection from the wire axis is defined by solving the system of equations:

Table 1 – Correlation of equation (9) values for circular current frequency $f = 8$ and 20 MHz

f, Hz	$\omega\tau$, s^{-1}	ω^2, s^{-2}.	$4\pi\omega_M$, s^{-1}.	$4\pi\omega_M^2$, s^{-2}	$\omega^2/4\pi\omega_M^2$
$2{,}0\cdot10^7$	$4{,}0\cdot10^6$	$4{,}0\cdot10^{14}$	$1{,}1053\cdot10^{11}$	$9{,}73\cdot10^{19}$	$3{,}62\cdot10^3$
$8{,}0\cdot10^6$	$1{,}6\cdot10^6$	$6{,}4\cdot10^{13}$	$1{,}1053\cdot10^{11}$	$9{,}73\cdot10^{19}$	$5{,}79\cdot10^2$

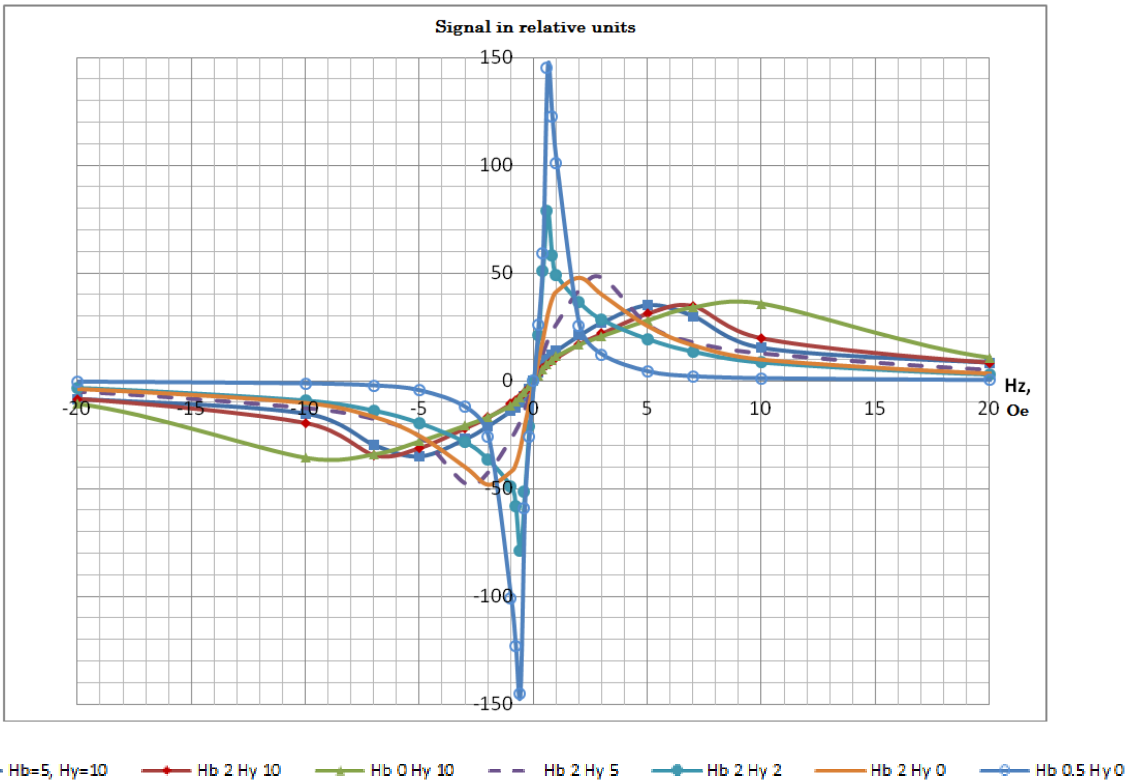

Fig. 7 – Dependence of microwire signal (in relative units) on value of longitudinal component of external magnetic field at various parameters H_b, H_y (H_k = 1 Oe)

$$\begin{aligned} & dE/d\psi = -M[H_b cos\psi sin(\phi-\varphi) + \\ & H sin\theta cos\psi sin\phi - H cos\theta sin\psi] - \\ & -2K[sin\psi sin(\phi-\varphi) cos\psi_K + \\ & + cos\psi sin\psi_K]\cdot[cos\psi sin(\phi-\varphi) cos\psi_K - \\ & - sin\psi sin\psi_K] + 4\pi M^2 sin\psi cos\psi cos^2(\phi-\varphi) = 0, \end{aligned} \tag{16}$$

$$\begin{aligned} & dE/d\phi = -M[H_b sin\psi cos(\phi-\varphi) + \\ & + H sin\theta sin\psi cos\phi] - \\ & -2K[sin\psi sin(\phi-\varphi) cos\psi_K + \\ & + cos\psi sin\psi_K]\cdot sin\psi cos(\phi-\varphi) cos\psi_K - \\ & -4\pi M^2 sin^2\psi sin(\phi-\varphi) cos(\phi-\varphi) = 0. \end{aligned} \tag{17}$$

Since the energy of the magnetic anisotropy of the wire is described by the relation, which is similar to magnetically uniaxial anisotropy, helical anisotropy usually expresses with the so-called effective magnetic anisotropy field $H_K \equiv 2K/M$. Although this concept is only for the vector which is introduced for small deviations of $\boldsymbol{M}$ from easy magnetization axis, the value of H_K may be measured in experiment and it is put as a parameter in the final material anisotropy calculation formulas.

Because of the smallness of the angle ψ_K the system of equations for determining equilibrium angle of magnetization vector $\boldsymbol{M}$ deviation in terms of the effective magnetic anisotropy field the system of equations takes the form:

$$\begin{aligned} & dE/d\psi = -M[H_b cos\psi sin(\phi-\varphi) + \\ & H sin\theta cos\psi sin\phi - H cos\theta sin\psi] - \\ & -2K[sin\psi sin(\phi-\varphi) + \\ & + cos\psi \cdot \psi_K]\cdot[cos\psi sin(\phi-\varphi) - \\ & - sin\psi \cdot \psi_K] + 4\pi M^2 sin\psi cos\psi cos^2(\phi-\varphi) = 0, \end{aligned} \tag{18}$$

$$\begin{aligned} & dE/d\phi = -M[H_b sin\psi cos(\phi-\varphi) + \\ & + H sin\theta sin\psi cos\phi] - \\ & -2K[sin\psi sin(\phi-\varphi) + \\ & + cos\psi \cdot \psi_K]\cdot sin\psi cos(\phi-\varphi) - \\ & -4\pi M^2 sin^2\psi sin(\phi-\varphi) cos(\phi-\varphi) = 0. \end{aligned} \tag{19}$$

Numerical solution of this system allows to find the distribution of magnetization in the case of a helical anisotropy and to determine the conditions that minimize the influence of transverse components of the magnetic field on the sensor signal.

4. CONCLUSIONS

Modeling of the influence of external magnetic fields on the orientation of the magnetization vector and its distribution in the skin-layer of microwire allows to interpret experimental data and to analyze the possibilities of constructing 3D smart sensors of weak magnetic fields.

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