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On Influence of Magnetic Fields and Excitation Conditions on the Magnetization Distribution in Microwire Magnetoimpedance Element

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One of important condition for the successful development of effective magnetic field sensors based on amorphous ferromagnetic microwires is to identify factors affecting the reversal processes in the surface layer of the magnetoimpedance wire. In this paper, the distribution of magnetization is considered as a function of the magnetic properties of the wire material, current flowing through it, strength and orientation of the external magnetic field. The impact of these factors on the performance of the sensor is analyzed on the basis of the numerical simulation of the sensor element

Keywords: Amorphous magnetic microwire, Magnetoimpedance element, Magnetization, Circumferential (helical) magnetic anizotropy, Magnetic field, Bias current (field).

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1. INTRODUCTION

The actual problem of microsystems technology is the development of sensors for weak magnetic fields and currents [1]. Magnetoimpedance (MI) effect allows you to create sensors that exceeding in its capabilities / surpasses the capabilities of devices that are based on the widely known magnetoresistive effect [2, 3]. The MI effect is most strongly manifested in cylindrical amorphous wires in which the magnetic anisotropy of a specific structure is formed for high output signal values. Such anisotropy results to a predominantly circular or spiral (helical) distribution the saturation magnetization in the outer layer of the conductor, whereas it is parallel to the axis of microwire in its core. It is assumed that during the flow of AC the magnetodynamics of such system is due to small oscillations of the magnetization vector with respect to its stationary position. External magnetic field 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.

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

2. MAGNETIZATION DISTRIBUTION IN THE SKIN LAYER OF THE WIRE UNDER THE INFLUENCE OF MAGNETIC FIELDS

Here, formulation of the problem of the distribution of the magnetization as a function of the material parameters of the conductor, the excitation mode (bias current) and external conditions (intensity and orientation of the external magnetic field) is considered in its most general form.

The picture of magnetization distribution in the skin layer is shown in Fig. 1 for the case of a helical anisotropy and arbitrary direction of the external field. In the experiment geometry, the conductor axis z is the polar axis of the spherical and cylindrical coordinate systems. Easy magnetization direction in the skin layer depicted spiral lines. Point O on the cylindrical surface of the wire is site where the current state of magnetization is examined, it is also the beginning of the coordinate system $x'y'z'$. Its position in the xy plane is specified by azimuth angle of the polar coordinate system φ. Equilibrium orientation of the magnetization vector $\boldsymbol{M}$ is described polar and azimuthal angles (ψ, ϕ) in the system $x'y'z'$. Ones are determined by the material parameters of the conductor, current flowing through it and the external magnetic field $\boldsymbol{H}$. θ is the deviation angle of the vector $\boldsymbol{H}$ from the axis of the conductor in the z-axis direction y. Direction of the easy magnetiza-

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tion axis at point O determined by the tangent $\overleftrightarrow{K}$ to the helical line of easy magnetization, and the pitch of the helix defined by the angle ψ_K between the tangent and the plane $x'Oy'$. The projection of the tangent to this plane makes the angle φ with the axis y'.

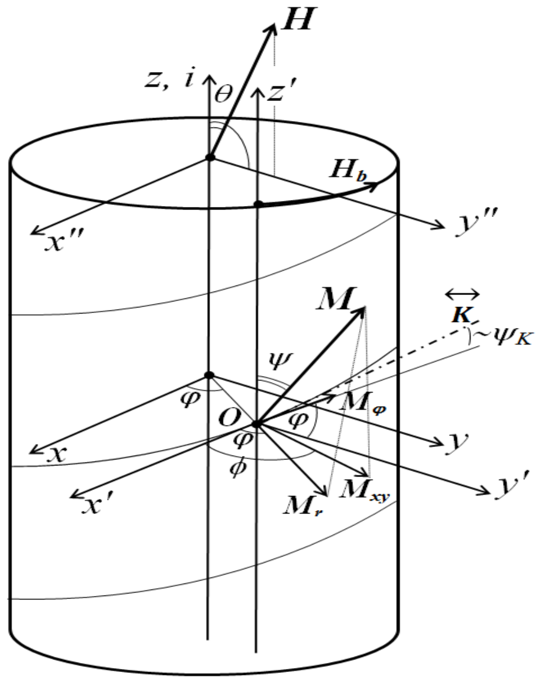

Fig. 1 – Geometry and main features of the MI element

Domain structure complicates the picture of the magnetization distribution in the wire. Therefore, it are usually suppressed by the magnetic bias field $\boldsymbol{H_b}$ generated by the DC component of the excitation current which magnetizes the wire in a circular direction. The circular field on the surface can be estimated by calculating formula: $H_b = i / a$, when H_b is magnetic field [Oe], i is electric current [mA], $2a$ – diameter of the wires core (μm).

The tangential component of $\boldsymbol{M}$ does not create the demagnetizing fields and does not contribute to the magnetostatic energy. In the general case ($H_y \neq 0$), there is radial component of the magnetization, which leads to increase in the magnetostatic energy. The total energy of the system is $E = E_H + E_K + E_M$ where the magnetostatic energy is $E_M = \sum N_j M_j^2 / 2$, Zeeman energy is $E_H = -\boldsymbol{M}\boldsymbol{H}_t$, anisotropy energy is $E_K = K\sin^2\left(M\vec{K}\right) = K\left[1-\cos^2\left(M\vec{K}\right)\right]$, $\boldsymbol{H}_t = \boldsymbol{H} + \boldsymbol{H_b}$, K is anisotropy constant; N_j are components of demagnetizing factor. The vector components of the magnetic field $\boldsymbol{H}$ and the magnetization $\boldsymbol{M}$ can be written in terms of Cartesian, spherical and cylindrical coordinates:

$$H_{tx} = -H_b\sin\varphi,\ H_{ty} = H_b\cos\varphi + H\sin\theta,\ H_{tz} = H\cos\theta, \quad (3)$$

$$M_x = M\sin\psi\cos\phi,\ M_y = M\sin\psi\sin\phi,\ M_z = M\cos\psi; \quad (4)$$

$$M_r = M_{xy}\cos(\phi-\varphi) = M\sin\psi\cos(\phi-\varphi), \quad (5)$$

$$M_\varphi = M\sin\psi\sin(\phi-\varphi). \quad (6)$$

In this case, $N_\varphi = N_z = 0$, $N_r \approx 4\pi$, so

$$E_H = -M\begin{bmatrix} H_b\sin\psi\sin(\phi-\varphi) + \\ +H\sin\theta\sin\psi\sin\phi + H\cos\theta\cos\psi \end{bmatrix}, \quad (7)$$

$$E_K = K\left\{1-\left[\sin\psi\sin(\phi-\varphi)\cos\psi_K + \cos\psi\sin\psi_K\right]^2\right\}, \quad (8)$$

$$E_M = 2\pi M^2\sin^2\psi\cos^2(\phi-\varphi). \quad (9)$$

The solution of equation system derived from the conditions for the extremum of the total energy:

$$\partial E / \partial\psi = 0,\ \partial E / \partial\phi = 0 \quad (10)$$

in general is a challenging task. Some simplification can be achieved by assuming a circular nature of anisotropy: $\psi_K = 0$.

For typical parameters of the MI sensor material ($H_K = 1 \ldots 5$ Oe, $M \sim 500$ G, core diameter 15-40 microns), measured external field H (up to 10 Oe) and field currents i (up to 50 mA and, respectively, H_b up to 6 Oe), that we used in the construction studied sensors, there are following relations:

$$4\pi M >> H, H_K, H_b, E_M >> E_H, E_K.$$

Thus, there are no factors that would lead to the emergence of a significant magnetization M_r in the radial direction on any site of the wire surface. Consequently, the contribution of the demagnetizing fields in the energy of the system is very small, and the vector $\boldsymbol{M}$ can only slightly deviate from the tangent direction to the surface of the wire, that is $\phi \approx \varphi \pm 90^o$, $\phi - \varphi \approx \pm 90^o$, $\sin(\phi - \varphi) \approx \pm 1$, or

$$\sin\phi \approx \pm\cos\varphi, \cos\phi \approx \mp\sin\varphi. \quad (11)$$

Choice of the sign in front of H_K depends on the relation field values H_b and H_y affecting the inclination direction of the vector $\boldsymbol{M}$. There are two possibilities for orientation of effective anisotropy field $\boldsymbol{H_K}$ in the plane of the wire cross-section with respect to the transversal direction of the wire contour. Wherein, the effect of the anisotropy field coincides with a direction of the dominant factors for the surface points $-90^o < \varphi < 90^o$ (i.e. $0^o < \varphi < 90^o$ and $270^o < \varphi < 360^o$). In this case the components of all three fields are added. With multidirectional action of the fields H_y and H_b (for $90^o < \varphi < 270^o$), H_K added to the field whose value along a given axis is higher. The components of total effective field are:

$$H_{\varphi\Sigma} = H_y\cos\varphi + H_b + H_K\frac{\left|H_b + H_y\cos\varphi\right|}{H_b + H_y\cos\varphi}, \quad (12)$$
$$H_{K\Sigma} = H_y\sin\varphi$$

in cylindrical coordinate system or

$$H_{x\Sigma} = -\left(H_b + H_K\right)\sin\varphi,$$
$$H_{y\Sigma} = H_y + \left(H_b - H_K\frac{\left|H_b\cos\varphi + H_y\right|}{H_b\cos\varphi + H_y}\right)\cos\varphi \quad (13)$$

in Cartesian coordinates.

Critical point of transition from one regime to another is determined by the vanishing of the resultant contributions of H_b and H_y in the extremum condition $\partial E / \partial \psi = H_b \sin(\phi - \varphi) + H_y \sin\phi = 0$.

Taking into account the relationship (11) between ϕ and φ we obtain:

$$\cos\varphi = - H_b / H_y. \qquad (14)$$

The solution domains to the problem is shown schematically in Fig. 2 according to the position on the wire surface φ and to the contribution sign of different factors.

With that said, from (10) we obtain the system of equations:

$$\begin{aligned} &\pm (H_b + H_y\cos\varphi)\cos\psi\, y - H_z\sin\varphi + \\ &+ [H_K - (H_K + 4\pi M)\cos^2(\phi - \varphi)]\sin\psi\cos\psi = 0 \end{aligned}, \qquad (15)$$

$$[H_b \pm (H_K + 4\pi M)\sin\psi]\cos(\phi - \varphi) + H_y\cos\phi = 0. \qquad (16)$$

Transformation of this system for $4\pi M >> H_K$ finally yields a transcendental equation for finding angle ψ:

$$\begin{aligned} &\pm (H_b + H_y\cos\varphi) - H_z \mathrm{tg}\psi + [1 - (4\pi M / H_K)\times \\ &\times \left(H_y \sin\varphi\right)^2 / (H_b \pm 4\pi M \sin\psi)^2] H_K \sin\psi = 0 \end{aligned} \qquad (17)$$

where the lower sign corresponds to the condition:

$$\arccos(- H_b / H_y) < \varphi < 360° - \arccos(- H_b / H_y). \qquad (18)$$

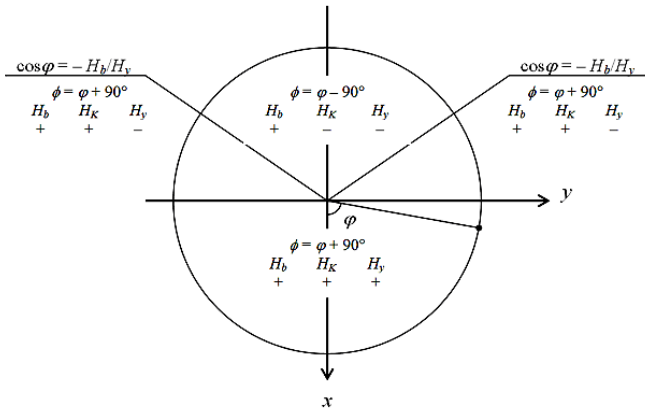

Fig. 2 – The solution domains to the angle φ

At the critical point $\varphi_1 = - \arccos(- H_b / H_y)$ we have:

$$\begin{aligned} &\cos\psi = H_z / \{[1 - (4\pi M / H_K)(H_y \sin\varphi)^2 / \\ &/(H_b \pm 4\pi M \sin\psi)^2] H_K\} \end{aligned}. \qquad (19)$$

In cases of practical importance ($4\pi M >> H$, H_K, H_b) expression (19) simplifies to

$$M_z / M = \cos\psi = H_z / H_K. \qquad (20)$$

Fig. 3 shows an example of the obtained numerical solution of equation (18) for the magnetization distribution in the skin layer $M_z / M = \cos\psi$ as a function of magnetic fields for different positions on the wire surface. The wire parameters were $H_K = 1$ Oe, $4\pi M = 500$ G. When $\varphi = 0$ the transverse component of the external magnetic field H_y amplifies the angle of deflection of the magnetization from the wire axis similar to the action of field H_b, created by permanent component of the current in the wire (bias current). In points $\varphi = 90^{\circ}$ and 270° at same values H_b, the angle ψ is independent of H_y. If $\varphi = 180^{\circ}$ the fields H_y and H_b have the same effect on ψ, but they have the opposite action on the azimuthal direction of magnetization ϕ. Therefore at the same value of the circular bias field H_b, angle ψ either increases or decreases with the change of the transverse field H_y depending on the ratio H_b / H_y (while $H_y < H_b$ the transverse field reduces the deviation of the magnetization from the axis, the further growth of H_y it increases). At critical points $\varphi = \arccos(- H_b / H_y)$ ψ is independent of H_y. For illustration, the graph for points $\varphi = 120^{\circ}$ is shown in Fig. 3a which corresponds to the critical value of the azimuth angle φ_1 for $H_b / H_y = 0{,}5$. When the ratio $H_b / H_y = 0{,}2$, φ_1 is equal $101{,}5^{\circ}$. In this case the orientation of the magnetization vector at the same points on the wire surface depends strongly on the transverse component of the external magnetic field.

Assuming a homogeneous distribution of current density in the skin layer, signal MI is proportional to the average value of function $\sin 2\psi = f(H_z)$ with bypassing along the wire contour. It may be obtained by numerical integration. Fig. 4 shows a graph of this function for the points defined by the condition $\varphi = 0$. For sensors it is interesting the linear part of the characteristics observed in $H_z < H_K$, so the descending branch of the graph, the corresponding values of $\psi < 45^{\circ}$ is not used. Consequently, the term in square brackets in (17) is close to 1, and for sensor applications equation can be written in a simplified form:

$$\pm (H_b + H_y\cos\varphi) - H_z \mathrm{tg}\psi + H_K \sin\psi = 0. \qquad (21)$$

CONCLUSIONS

It obtained the distribution of the magnetization in the magnetoimpedance conductor with the influence of different magnetic fields. This allows define the conditions under which the transverse component of the external magnetic field has no significant effect on the signal of the sensor element, and offers opportunities for constructing 3D smart sensors of magnetic fields.

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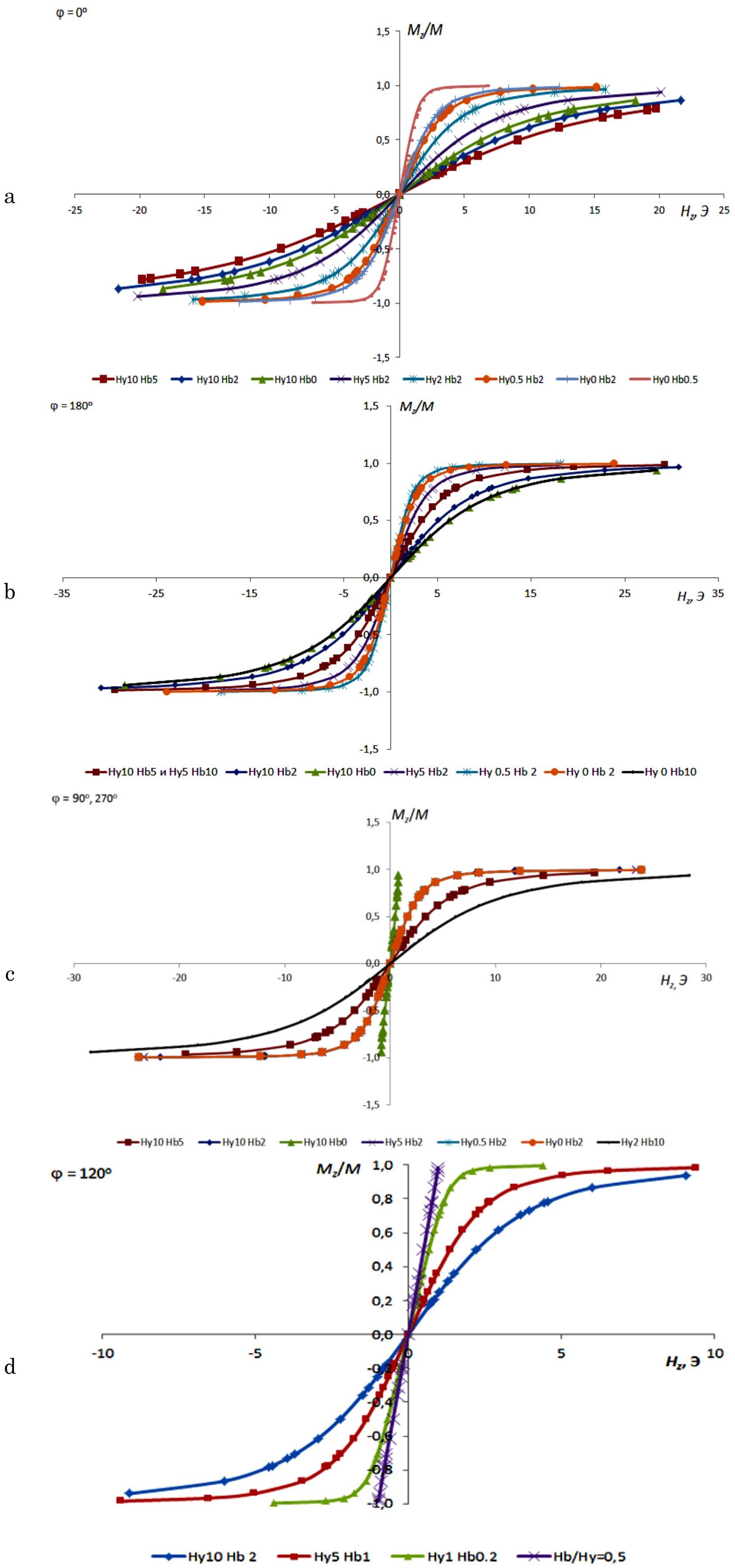

Fig. 3 – Relative value of the axial magnetization on the surface of wire with material parameters $H_K = 1$ Oe, $4\pi M = 500$ G for different values of the external (H_z and H_y) and circular (H_b) magnetic fields (Oe). Characteristic points determined by following

azimuth angles φ: a – 0º; b – 180º; c – 90º and 270º; d – 120º (φ = arcos (– H_b / H_y) for H_b / H_y = 0,5)

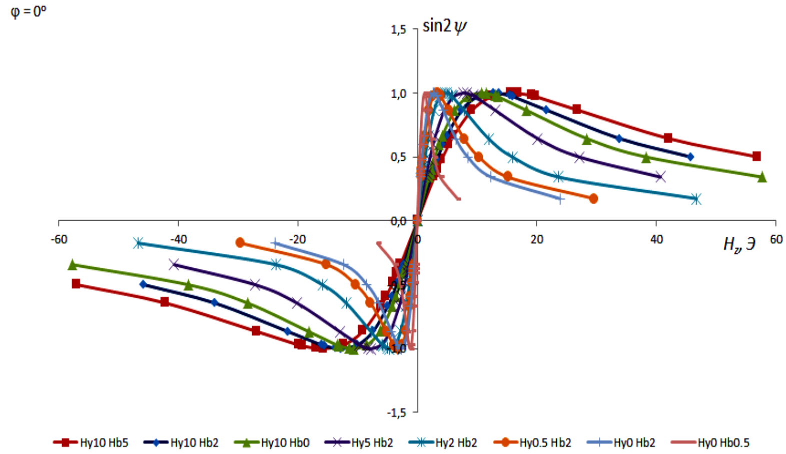

Fig. 4 – Graph of the function $\sin2\psi = f(H_z)$ for points on the surface of the MI conductor defined by $\varphi = 0$

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