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Off-Diagonal Magnetoimpedance in Amorphous Wires and Its Application in Miniature Sensors of Weak Magnetic Fields

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Abstract—Off-diagonal magnetoimpedance in amorphous cobalt-based microwire with helical magnetic anisotropy is investigated using a DC bias current. It is demonstrated that the circular magnetic field generated by the bias current improves the sensitivity to an axial external magnetic field, raises the output voltage peak, and expands the sensed field in which the peak is observed. However, a further increase in the bias current reduces the sensitivity. The experimental results agree qualitatively with the theory for large bias fields when the hysteresis in static magnetization is eliminated.

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INTRODUCTION

Developing noncryogenic technologies for miniaturized measurement systems with high sensitivity and resolution is an important branch of magnetometry. The magnetoimpedance effect (MI) in thin magnetic wires and films allows us to achieve a resolution of 30 nOe/Hz$^{1/2}$ with sensing element sizes on the order of millimeters [1, 2]. The MI effect is the change in the voltage at the ends of a magnetic wire with a high-frequency current; it occurs when the wire's magnetic structure is modified by, e. g., an external (measured) magnetic field. Significant changes in impedance are observed for transverse magnetic anisotropy (with respect to the conductor axis) [3, 4]. However, MI characteristics that are symmetrical with respect to the field display nonlinear behavior in a near-zero field. The operating point of the sensing element must be shifted to the linear region to measure weak magnetic fields, greatly complicating sensor design.

Employing off-diagonal impedance is a better solution for achieving the linear output characteristic. As usual, the MI element is excited by a HF current, and the signal is acquired from a coil wound on it [5–7]. The direction of the current in the coil changes along with the direction of the field; the output signal is antisymmetric with respect to the external magnetic field, and in the vicinity of zero field its behavior is linear. However, this antisymmetric behavior results in an off-diagonal MI signal of zero when the domain structure contains circular regions with opposite magnetizations. Magnetic biasing in the circular dimension must be used to eliminate the domain structure. In the case of helicoidal anisotropy, the signal remains even when there is a domain structure but is field-shifted, and the sensor's characteristic is asymmetric. In this work, we study the effect of a circular bias field on the off-diagonal MI characteristics of an amorphous microwire with helicoidal anisotropy.

Excitation with a pulsed current that contains both low- and high-frequency harmonics is often used in MI sensors. The direct component of the exciting current is important in eliminating the domain structure, which lowers the noise and enhances the signal (in the off-diagonal scheme of acquisition). The pulsed excitation of an MI sensor is usually accomplished with the aid of an integrated-circuit inverter [8, 9] or a microcontroller [10, 11]. Despite the simplicity of the scheme, pulse generation is described by a great many input parameters: the peak value of the exciting current, the frequency of repetition, and the length and shape of a pulse, all of which affect a sensor's characteristics. The complexity of allowing for all of these factors makes it difficult to find the optimum excitation parameters. In this study of the effect the pulse shape and low-frequency excitation components have on a signal (i.e., the off-diagonal impedance effect), we used a multifunction generator capable of establishing excitation signal characteristics. This allowed us to investigate the effect individual excitation parameters have on an off-diagonal MI in the sensor configuration.

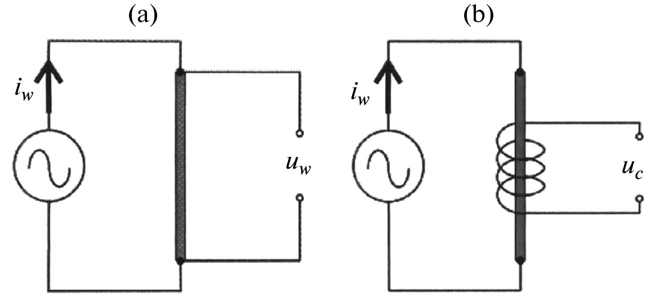

Fig. 1. Scheme for achieving the MI effect. A high-frequency signal induced by an alternating current can be measured (a) at the conductor's ends or (b) in the coil.

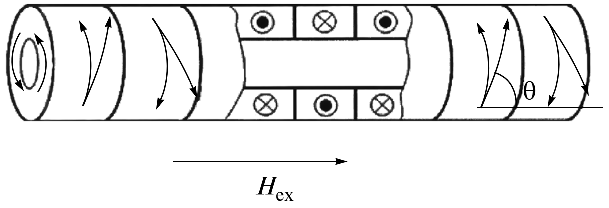

Fig. 2. Domain structure in an amorphous microwire with negative magnetostriction and circular anisotropy in the outer layer.

RESULTS AND DISCUSSION

Off-Diagonal MI in Amorphous Ferromagnetic Microwires

Alternating current in a magnetic conductor induces a tension signal at the conductor's ends (U_w) and in the coil (U_c) wound on the conductor (Fig. 1). Both voltages are expressed through a surface impedance matrix. With a certain magnetic structure, the surface impedance is sensitive to external influences (static magnetic field, mechanical strain, temperature); this is used in constructing high-sensitive magnetic detectors. The scheme in Fig. 1b is the one that is preferred, as will be shown below.

Surface impedance $\hat{\xi}$ is a factor in the vector relation between the tangential components of the electric $\vec{e}$ and magnetic $\vec{h}$ fields on the conductor's surface:

$$\vec{e}_t = \xi(\vec{h}_t \times \vec{n}). \qquad (1)$$

where $\vec{e}_t$ and $\vec{h}_t$ are the tangent vectors of the electric and magnetic fields on the conductor surface, respectively; $\vec{n}$ is the unit normal vector directed toward the surface. For a cylindrical conductor, tensions U_w and U_c are determined using the axial $\vec{e}_z$ and circular $\vec{e}_\varphi$ components of the electric field, respectively. Allowing for the impedance correlation between fields (1) and the uniformity on the wire surface, we obtain

$$U_w = e_z l = \xi_{zz} h_\varphi l = \xi_{zz} li/(2\pi a), \qquad (2)$$

$$U_c = e_\varphi 2\pi an = \xi_{\varphi z} h_\varphi 2\pi an = \xi_{\varphi z} ni. \qquad (3)$$

where $h_\varphi = i/(2\pi a)$ is the circular magnetic field on the surface; ξ_{zz} and $\xi_{\varphi z}$ are the corresponding components of tensor $\hat{\xi}$ in cylindrical coordinates; l is the wire length; a is the wire radius; and n is the number of turns in the coil. Equations (2) and (3) may be considered a generalization of Ohm's law for a magnetic conductor at high frequencies:

$$U_w = iZ, \qquad (4)$$

$$U_c = iZ_{\text{off}}, \qquad (5)$$

where the notations for diagonal $Z = \xi_{zz} l/(2\pi a)$ and off-diagonal $Z_{\text{off}} = \xi_{\varphi z} n$ impedances are used.

Tensor $\hat{\xi}$ is found by solving the electrodynamic problem (Maxwell's equations) along with the equation of motion for magnetization (the Landau–Lifshitz equation) [5]. We assume that the wire has uniform electromagnetic properties and helicoidal static magnetization that is tangental to the surface and forms angle Θ with the wire axis. The tensor on the surface is then constant, and its components in the approximation of a strong skin effect are

$$\xi_{zz} = \xi_0((\mu_{\text{eff}})^{1/2}\cos^2\Theta + \sin^2\Theta), \qquad (6)$$

$$\xi_{\varphi z} = -\xi_0((\mu_{\text{eff}})^{1/2} - 1)\cos\Theta\sin\Theta. \qquad (7)$$

where ξ_0 is the surface impedance of a nonmagnetic metal; μ_{eff} is the circular component of the magnetic permeability tensor in the coordinate frame with the polar axis directed along the static magnetization. The method for calculating μ_{eff} was described in detail in [5]. Since the impedance tensor depends on both a material's permeability and the direction of static magnetization, the induced signal can be controlled via conductor magnetization. Stationary magnetization is much more sensitive to an external static magnetic field than a change in magnetic permeability. This is observed in sensing elements that use magnetic impedance. It is worth noting that the off-diagonal component of the impedance tensor arises solely due to magnetic properties. Furthermore, it changes sign when the direction of either the circular or axial projection of static magnetization is changed. This behavior produces a voltage signal that is linear with respect to the measured magnetic field.

Near circular anisotropy is observed in amorphous cobalt-based microwires, which often have negative magnetostriction. This leads to the formation of the circular domain structure shown in Fig. 2. An external magnetic field applied along the wire axis deflects the magnetization vector in the domains toward the axis. However, since the values of $\sin\Theta$ in adjacent domains have opposite signs, the voltage in the coil is averaged over the domains to zero for any H_{ex}. Of course, this is true only when there is ideal circular anisotropy. If the anisotropy axes shift slightly from the circular direction, the off-diagonal signal is still non-zero but is much weaker than the diagonal signal. To avoid this,

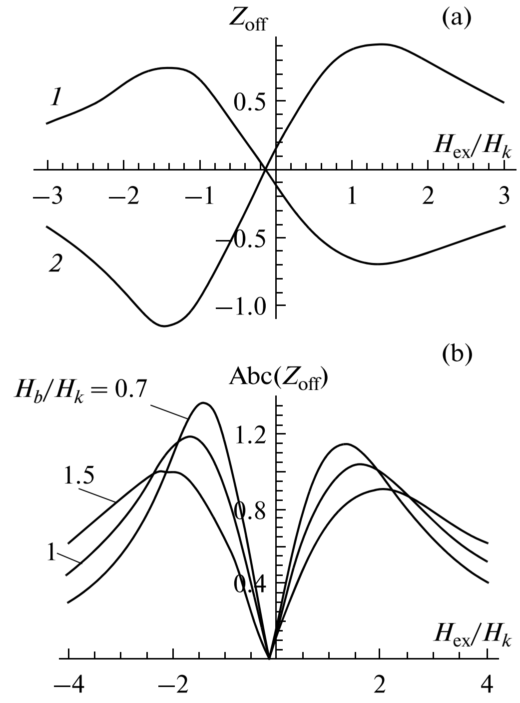

Fig. 3. Field dependences of off-diagonal impedance at 10 MHz with a bias field: (a) real and imaginary parts of the off-diagonal impedance at $H_b/H_k = 0.7$; (b) values of the off-diagonal impedance at different intensities of the circular bias field.

the domain structure must be eliminated using, e.g., a DC bias current that produces a circular magnetic field. Optimum biasing is achieved with circular coercivity. Figure 3 shows the theoretical field dependences of off-diagonal impedance calculated with Eq. (7) for a single-domain wire having near-circular anisotropy (anisotropy angle $\alpha = 82°$) in circular bias field H_b. The behavior of the real and imaginary parts of the off-diagonal impedance when $H_b/H_k = 0.7$ (and there is no rotational hysteresis) is described in Fig. 3a, which shows the change in sign that accompanies the one in external field intensity. The curves pass through zero at some negative field value, due to the deviation of the anisotropy from the circular direction. Figure 3b present the field dependences of the absolute values of off-diagonal impedance for different circular bias fields. The sensitivity of impedance variation with respect to the external field obviously falls as the field grows, due to an increase in the magnetic rigidity in the circular direction.

Method for Investigating an Off-Diagonal MI

The effect different parameters of excitation have on an off-diagonal MI was investigated using the instrument shown in Fig. 4. An alternating current in the form of pulses or harmonic oscillations with different continuous components (bias current) from a functional generator is applied to a microwire. The continuous component determines the circular bias field. The wire with the coil from which the signal is taken are placed into a long solenoid, generating magnetic field H_{ex} that varied in the range of ±60 Oe. The dependence of the output voltage on the field was recorded on a digital oscilloscope.

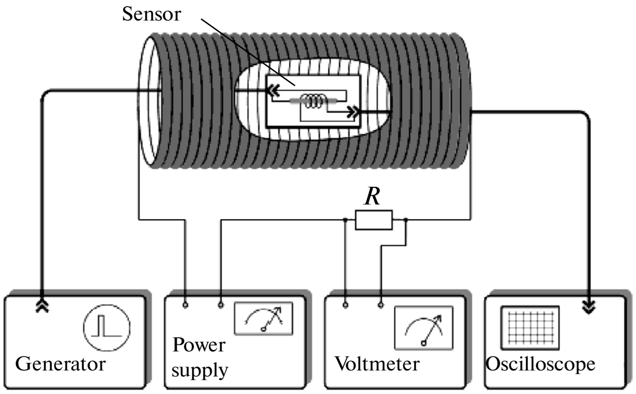

Fig. 4. Experimental setup for investigating off-diagonal MIs.

Amorphous wire made of $Co_{66.94}Fe_{3.83}Ni_{1.44}B_{11.57}Si_{14.59}Mo_{1.69}$ with a glass coating was used as our MI element. The metal conductor's diameter was 16 μm; the complete outer diameter was 16.8 μm. The wire was fixed on a paper-based laminate substrate. In the off-diagonal MI configuration, high-frequency excitation was applied to a magnetosensitive element. The output signal was acquired from a coil containing 40 turns of a copper wire 40 μm in diameter, wound onto the substrate with the MI wire. The studied structure corresponded to a practical sensing element 3.2 × 1.8 × 0.5 mm in size. A schematic representation of the magnetosensitive element is given in Fig. 5.

Two types of signal were used to excite the MI wire: pulsed and harmonic with a varied DC bias current. The sensing unit (the MI wire with the coil) forms an

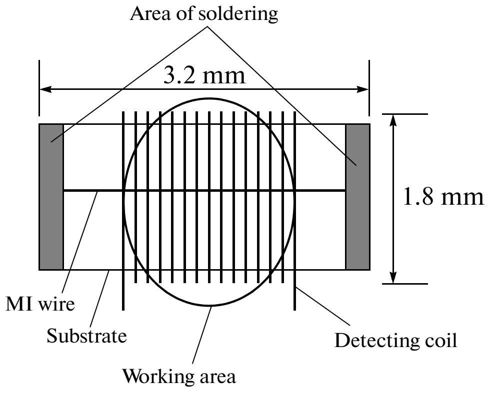

Fig. 5. Structure of an off-diagonal MI element.

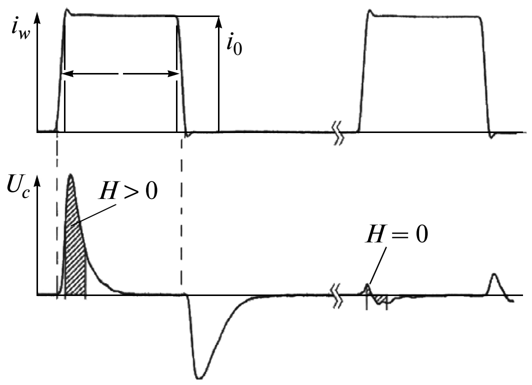

Fig. 6. Shapes of the excitation signal (upper part) and output signal (bottom part) for an off-diagonal MI element. The rise and fall times of the excitation pulse are 20 ns.

LC tank with a resonance frequency of 8 MHz and the actual structure parameters. The output voltage is highest at this frequency of sinusoidal excitation, and the signal is not distorted. This justified our choice of the excitation frequency.

Experimental Results and Analysis

If the wire is excited by separate rectangular pulses (Fig. 6) with rise and fall times much shorter than the pulse length, the voltage on the detecting coil when there is an external field has the form of two sharp peaks of opposite polarities. If the field direction changes, the output signals polarity changes as well. If there is no external field, the output signal falls considerably, demonstrating the antisymmetric character of the off-diagonal impedance and the drop in signal in a zero field; however, studying the effect of the low-frequency components that determine the circular bias field is quite difficult.

A regime with the superposition of harmonic excitation and DC bias current was used to find the conditions for optimum circular biasing. The dependences of the output signal's amplitude on the external field when using different bias currents are plotted in Fig. 7. The current that generates the circular field of lower intensity than the anisotropy field (curve *2* in the plot; the circular field on the surface is 1.9 Oe) greatly improves the maximum signal intensity, but further growth of the bias current lowers the maximum value and signal sensitivity. This behavior agrees with the theoretical dependences shown in Fig. 3b. The asymmetry of the signal acquired from a sensor in fields with positive and negative polarities is due to helicoidal anisotropy. An unexpected feature of the MI effect when there was no bias field was revealed: the output signal amplitude and the detector's sensitivity in fields in the range of ±2 Oe were comparable to those when there was a bias current. This could be due to the axial field also affecting the domain structure when there is helicoidal anisotropy.

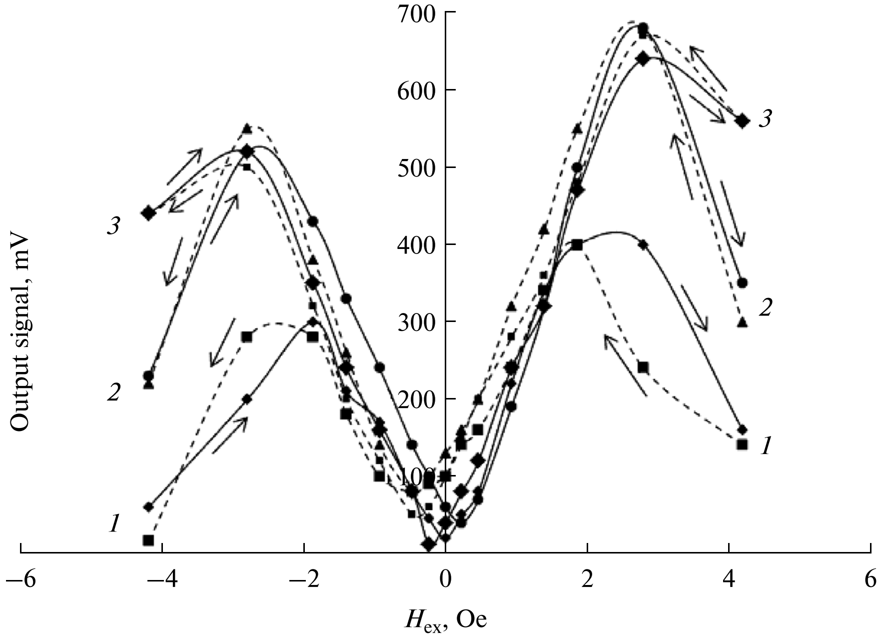

Fig. 7. Dependences of the signal from an off-diagonal MI sensor on a longitudinal field with different bias fields in the microwire. The circular magnetic field assumes values of (1) 0, (2) 1.95, and (3) 5.2 Oe. The signal was measured with the field changing from high negative values to positive values and back again; the reverse dependences are plotted with dashes.

CONCLUSIONS

The main aim of this work was to study the effect a static bias magnetic field has on the characteristics of off-diagonal magnetoimpedance in amorphous microwires. A direct current in the wire that generates a circular bias field improves sensitivity by eliminating the domain structure and smoothing the effect of easy magnetization deviating from its primary direction, which is natural for wires with helicoidal anisotropy. It was found that the helicoidal anisotropy allows us to acquire the strong response of off-diagonal magnetoimpedance even when there is no bias current.

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