Temperature Instability of the Off-Diagonal Magnetoimpedance Sensors Based on Co-Rich Amorphous Microwires

Sergei Gudoshnikov, Vadim Tarasov, Vadim Mashera
National University of Science and Technology «MISiS»
Moscow, Russia
Email: gudosh@izmiran.ru, vptar@misis.ru,
masherovvadim@mail.ru

Vladimir Odintsov, Boris Liubimov
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, (IZMIRAN)
Troitsk, Moscow, Russia
Email: vodin@izmiran.ru, b.lubimoff@gmail.com

Yury Grebenshchikov
Financial University under the Government of the Russian Federation, (FU)
Moscow, Russia
Email: yugreb@izmiran.ru

***Abstract* — Temperature instability of the off-diagonal magnetoimpedance sensor is discussed based on experiments accomplished with Co-rich amorphous ferromagnetic microwire. The glass-coated microwire produced by the Tailor-Ulitovsky method of $Co_{69}Fe_4Cr_4Si_{11}B_{12}$ composition with an internal core of 6.8 µm and a glass shell of 14.7 µm radius was tested. The magnetoimpedance sensor was a 5 mm long piece microwire with a small pick-up coil of 80 turns wounded around the microwire. The saturation magnetization, anisotropy field of the microwire and off-diagonal component of impedance at 4 MHz frequency were investigated in the temperature range of −20 to +80 °C. The measured data were used to determine the influence of these parameters on the temperature dependence of the pick-up coil electro-motive force amplitude. It was found that the change of the offset drift near the zero magnetic field is ~ 0.125 (A/m)/°C and the coefficient of sensitivity is about +2.6%/ °C.**

Keywords — amorphous ferromagnetic microwires; magnetoimpedance; temperature stability.

I. INTRODUCTION

Recently, much attention has been paid to the study of the Giant Magneto-Impedance (GMI) effect in soft magnetic materials, which involves changes in the complex resistance of the ferromagnetic conductor *Z(H)*, when exposed to an external magnetic field *H*. The increased interest in the GMI effect is associated primarily with the possibility of creating on its basis inexpensive, miniature and highly sensitive magnetometers for various technical applications. Among the materials with the GMI effect, the best results were achieved in amorphous ferromagnetic microwires in a glass-coated microwire produced by the Tailor-Ulitovsky [1] method.

The best microwires are characterized by an ideal cylindrical shape, a small number of defects per unit length, a uniform distribution of magnetization and very small values of the magnetic anisotropy field (~ 100 A/m and less). In cobalt-rich microwires with a total radius of 5-15 micrometers, high values of the GMI ratio (ΔZ/Z ~ 600% [2]) have been obtained. Laboratory models of GMI magnetometers with an equivalent magnetic field noise level less than 10 $pT/Hz^{1/2}$ in the low frequency range from 0 to 1 kHz have been developed on the basis of such microwires [3][4]. One of the problems of such magnetometers is their strong temperature instability. Studies conducted by [5] have shown that the temperature instability of such magnetometers can be up to 100 nT per °C or more. To explain such a high temperature instability, a simplified model of the off-diagonal GMI effect is proposed in this work, and the results of the temperature studies of the GMI-sensor are presented.

The rest of the paper is structured as follows. Section II presents the description of the GMI sensor, research equipment and measurement methods. Section III describes the behavior of the GMI sensor in a temperature range of 20 °C to +80 °C, and a simplified model of the microwire's off-diagonal GMI effect. The results of modeling are compared with experimental data. Conclusions are given in Section IV.

II. MATERIALS AND METHODS

Measurements were carried out on a GMI sensor, in which 5 mm segment of the glass-coated microwire, radius of a ferromagnetic core r_0 of about 6.8 µm, total radius 14.7 µm and the composition of $Co_{69}Fe_4Cr_4Si_{11}B_{12}$ was used as a sensitive element [6]. To register the signals proportional to the off-diagonal impedance component $Z_{\varphi z}(f,H)$, a pick-up coil with radius 0.25 mm, containing N = 80 turns of copper wire with a diameter of 40 µm was wounded onto the microwire.

For the off-diagonal operation, the microwire was excited by sinusoidal current I_{ac} with a frequency of f = 4 MHz and amplitude of 1.0 mA. In addition, a small direct bias current $I_{dc.}$ = 2.0 mA was applied to the microwire. The scheme of excitation and registration of the GMI sensor signal is shown in Figure 1. The Electro-Motive Force (EMF) pick-up coil signal was amplified and then detected by a lock-in detector with 4 MHz reference signal. During GMI measurements, the GMI-sensor was placed within a solenoid powered by a linearly varying low-frequency current. The solenoid could generate the axial magnetic field of amplitude ± 1000 A/m. The temperature dependences of the off-diagonal GMI response versus the applied magnetic field and the offset drift were measured.

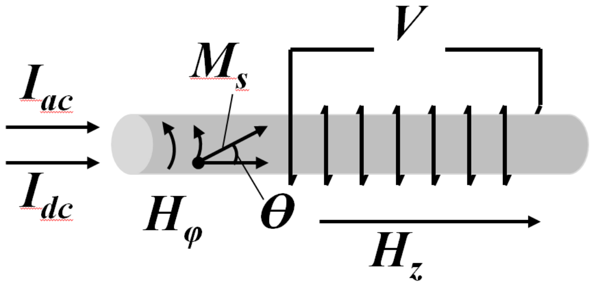

Figure 1. The scheme of excitation and registration of the GMI sensor signal.

At temperature measurements, the GMI sensor was placed inside the temperature chamber providing temperature in the range of -20 °C to +80 °C. To protect against external magnetic field, a magnetic shield with a shielding coefficient K ~ 1000 was used. The residual magnetic field in the magnetic shield did not exceed 50 nT.

Magnetic hysteresis loops of the microwires were measured using a conventional Quantum Design Physical Property Measurement System (PPMS) at the temperature range of -20 °C to +80 °C.

III. RESULTS AND DISCUSSIONS

A. *The temperature off-diagonal response of the GMI sensor*

Figure 2 shows the amplitude of 4 MHz EMF signals, induced in the pick-up coil, versus the longitudinally applied magnetic field H_z at different temperatures -20 °C, 20 °C and 80 °C. These curves correspond to the off-diagonal responses of the GMI sensor.

The inset in Figure 2 shows the behavior of the output voltage (in arbitrary units – a.u.) of the GMI sensor for two values of applied magnetic fields (0 A/m - circles, 13 A/m - squares) depending on the heating temperature. The output voltage grew monotonically with increasing temperature. The sensitivity $\Delta U/\Delta H$ for the low magnetic field region at -20 °C is 0.012 a.u./A/m and 0.032 a.u./A/m at 80 °C. This represents an increase of 260 % and corresponds to a temperature coefficient of sensitivity of +2.6%/ °C. The EMF offset (the top curve on the inset in Figure 2) varies from 0.06 a.u. at -20 °C to 0.156 a.u. at +80 °C. The difference corresponds to a change of 12.5 % of the full voltage scale at -20 °C. This change corresponds to a temperature coefficient of the offset drift of 0.125 A/m / °C (157 nT/°C).

B. *Low frequency model of the off-diagonal sensor*

To interpret the temperature behavior of the GMI sensor, we used a simplified model for the case of microwire excitation by Alternating Current (AC) I_{ac} with a relatively low frequency, when the skin depth is more than the microwire radius. In addition, it is assumed that at each point of the microwire, a magnetization reaches its limit value M_s and can change only in direction.

Under the above conditions, in the external longitudinal field H_z and circumferential field H_φ, the direction of the magnetization vector M_s at each microwire's point corresponds to the minimum energy and is determined by the equality:

$$h_1(\alpha, h) = \pm \frac{h-\alpha}{\alpha}\sqrt{1-\alpha^2}\,, \tag{1}$$

where: $h_1 = H_\varphi / H_a;\ h = H_z / H_a$ are dimensionless circumferential and longitudinal applied magnetic fields normalized on the anisotropy field of H_a, and $\alpha = M_z/M_s$ is a dimensionless component of the longitudinal microwire magnetization of M_z normalized to the saturation magnetization of M_s ($\alpha = \cos\theta$, Figure 1). The two signs in (1) correspond to different directions of azimuthal magnetization ($\sin\theta$). The equilibrium curves $h_1(\alpha)$ of equality (1) for three fixed values of h (04, 1.0, 1.6) are shown in Figure 3. A complete set of curves, similar to those shown in Figure 3, allows to determine the evolution of the microwire magnetization average value under the influence of circular and longitudinal magnetic fields.

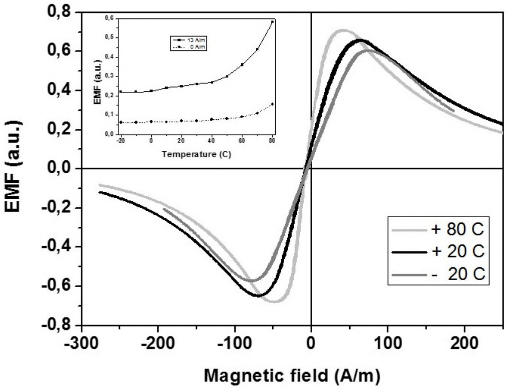

Figure 2. Experimental dependences of the off-diagonal EMF signals versus magnetic field at different temperatures. Inset shows the EMF signals for zero (circles) and applied magnetic fields 13 A/m (squares).

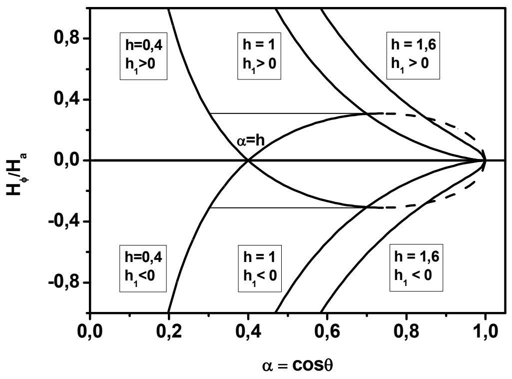

Figure 3. The equilibrium curves $h_1(\alpha)$ of equality (1) for three fixed values of h (0.4, 1.0, 1.6)

If AC current I_{ac} flows through the microwire, the azimuthal field H_φ generated by it will cause a periodic change in the average longitudinal magnetization M_z and create an alternating magnetic flux in the pick-up coil [7]: $\Phi = \pi r_0 \mu_0 M_s \bar{\alpha}$. Here, $\bar{\alpha}$ is the average magnetization across the microwire section, which is associated with external fields and its value on the microwire surface $\boldsymbol{\alpha_s}$ by the expression:

$$\bar{\alpha} = \begin{cases} \dfrac{2}{h_1^2}\left(-h - \dfrac{h^3}{6} + \dfrac{h}{2}\alpha_s{}^2 - \dfrac{\alpha_s{}^3}{3} - h\ln\left(\dfrac{h}{\alpha_s}\right) + \dfrac{h^2}{\alpha_s}\right), & h \le 1 \\ \dfrac{2}{h_1^2}\left(-h^2 - \dfrac{h}{2} + \dfrac{1}{3} + \dfrac{h}{2}\alpha_s{}^2 - \dfrac{\alpha_s{}^3}{3} - h\ln\left(\dfrac{h}{\alpha_s}\right) + \dfrac{h^2}{\alpha_s}\right), & h > 1 \end{cases} \tag{2}$$

The magnitude of the EMF pick-up coil is proportional to the time derivative of the magnetic flux Φ and is determined by the expression:

$$EMF(t) = -\pi\mu_0 M_s r_o^2 N \frac{\partial(\bar{\alpha})}{\partial t} \tag{3}$$

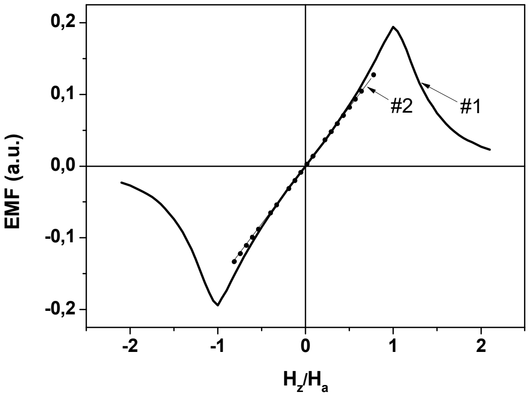

Figure 4. Calculated dependences of the EMF pick-up coil from the dimensionless longitudinal field using expressions (3) - #1 and (4) - #2.

The EMF response can be expanded in Fourier series in multiple frequencies f, $2f$, $3f$, … As an example, the EMF calculation result at the frequency f is shown in Figure 4, black line #1.

On the basis of the proposed model, it can be shown that the dependence of the EMF pick-up coil amplitude in the field region of $-H_a < H_z < +H_a$ (Figure 4) is approximately described by the following expression:

$$EMF \approx -\frac{\mathrm{M_s}}{\mathrm{H_a}}\frac{\mathrm{H}_z}{\mathrm{H_a}}\mathrm{N} r_0 \frac{\mathrm{dI}_{ac}}{\mathrm{dt}} \cdot \tag{4}$$

This dependence is shown in Figure 4 as a short dotted line #2. The expression in (4) contains only two parameters that depend on temperature. These are the saturation magnetization M_s and the anisotropy field H_a.

C. Temperature effect estimation

To simulate the temperature behavior of the GMI sensor, we measured the temperature dependences of relative saturation magnetization, $M_s/M_{s40}(T)$, and anisotropy field, $H_a(T)$. The results of these measurements are shown in Figure 5.

The temperature dependence of relative magnetization with an applied magnetic field of 10^4 A/m is presented in Figure 5 by square symbols (left axis). The data were normalized on the saturation magnetization measured at temperature -40 °C. Under heating treatment, the relative magnetization decreases slowly with increasing temperature from -20 °C to 100 °C. It varies between 0.96 at -20 °C and 0.82 at +100 °C, which is a decrease of 14%. This percentage corresponds to a temperature coefficient of 0.12%/°C.

The temperature dependence of the anisotropy field is presented in Figure 5 by circle symbols (right axis). The value of the anisotropy field for each temperature was determined as the value of the field corresponding to the maximum of the off-diagonal response (Figure 2). Under heating treatment, the anisotropy field decreases with increasing temperature from -20 °C to 80 °C. It varies between 75 A/m at -20 °C and 40 A/m at +80 °C., which is a decrease of 53%. This percentage corresponds to a temperature coefficient of 0.53%/°C.

Using the experimental data in Figure 5, we estimated the ratio of the coefficient $\mathrm{M_s/H_a^2}$ from expression (4) for temperature values -20 °C and +80 °C. This ratio is of order of 5.3/1.7 ~ 3.1. The same ratio for the sensitivity $\Delta U/\Delta H$, obtained from the experiment (part III.A.), gives value 0.156/0.06 = 2.6. The obtained agreement between the experimental and model data indicates the possibility of using the proposed approach for the analysis of the temperature properties of microwires.

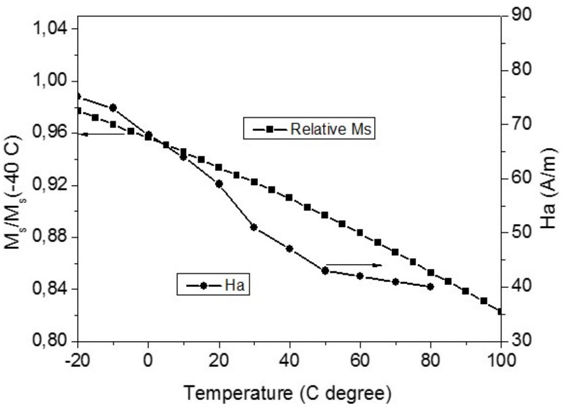

Figure 5. Temperature dependences of the relative saturation magnetization (squares) and anisotrpy field (circles).

IV. CONCLUSION

In conclusion, we have studied the problem of temperature stability of off-diagonal GMI sensors based on $Co_{69}Fe_4Cr_4Si_{11}B_{12}$ glass coated microwires. In the temperature range of −20 to +80 °C, the investigated microwires were characterized by high offset drift 0.125 (A/m)/°C and large temperature sensitivity +2.6%/ °C. The obtained temperature dependences off-diagonal response are satisfactorily explained in the framework of a simple model. The proposed model shows that the main sources of temperature instability of the GMI sensor are the temperature dependences of the saturation magnetization and anisotropy field of the microwire. The improvement of these parameters will increase the temperature stability of the GMI sensor. It is known that thermal treatment of microwires significantly affect the temperature behavior of GMI [8][9]. The data obtained show that the heat treatment should be carefully selected, according to the effect on the anisotropy field, to ensure the thermal stability of the microwires.

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