Experimental study of surface domain structure effects on off-diagonal magnetoimpedance in glass-coated Co-based microwires

V V Samsonova\textsuperscript{1,2}, A S Antonov\textsuperscript{1}, N A Buznikov\textsuperscript{3}, A A Rakhmanov\textsuperscript{1} and A P Zhukov\textsuperscript{4}

\textsuperscript{1} Institute for Theoretical and Applied Electrodynamics, Russian Academy of Sciences, Moscow 125412, Russia
\textsuperscript{2} Faculty of Physics, M V Lomonosov Moscow State University, Moscow 119992, Russia
\textsuperscript{3} Scientific-Research Institute of Natural Gases and Gas Technologies – VNIIGAZ, Razvilka, Leninsky District, Moscow Region 142717, Russia
\textsuperscript{4} Departamento Física de Materiales, Facultad de Químicas, Universidad del País Vasco/Euskal Herriko Universitatea, San Sebastián 20080, Spain

E-mail: samsonova@magn.ru

Abstract. The off-diagonal magnetoimpedance in glass-coated Co-based amorphous microwires is studied using a pick-up coil wound around the sample. The first and second harmonics in the pick-up coil voltage were measured as a function of the external magnetic field. It was observed that the first harmonic in the voltage corresponding to the linear off-diagonal magnetoimpedance was very small. This fact is attributed to the existence of the regular bamboo domain structure within a surface layer of the microwire. On the contrary, the second harmonic in the voltage differed from zero, which is related to the domain-walls motion.

1. Introduction
Glass-coated amorphous microwires are novel materials having unique magnetic properties and promising for sensor applications [1,2]. One of the striking phenomena observed in such materials is the giant magnetoimpedance (GMI). The GMI implies a strong dependence of the sample impedance on an external magnetic field [3]. Another method to detect the field-dependent signal consists in the use of the pick-up coil wound around a sample. This method is related to the cross-magnetization process, which appears since the current induces an axial magnetization variation. The effect has been referred to as the off-diagonal magnetoimpedance (ODMI). The ODMI has been observed and analyzed in detail in Co-based amorphous wires obtained by the rapid quenching process [4,5].

In this paper, the ODMI in glass-coated amorphous microwires is studied. The field dependences of the first and second harmonics in the pick-up coil voltage were measured. The second harmonic dominated in the frequency spectrum, whereas the first harmonic was vanishingly small. To increase the first harmonic signal, the bias current should be applied to the microwire. Analysis of the ODMI response allows one to conclude that the regular bamboo domain structure consisting of the domains with opposite circular magnetization direction exists within a surface layer of the studied samples.
2. Experimental

Glass-coated microwires of the nominal composition Co_{67.05}\text{Fe}_{3.85}\text{Ni}_{1.44}\text{B}_{11.53}\text{Si}_{14.47}\text{Mo}_{1.66} were used in experiments. The microwires fabricated by Taylor–Ulitovsky method had the amorphous core diameter of 24 \text{ \mu m}, and the glass coating thickness was 3.1 \text{ \mu m}. The samples had the length of 3.8 mm.

Hysteresis loops were obtained by an induction method [6] and by using the vibrating sample anisometer (VSM). The GMI and ODMI were measured by means of HP4395A Spectrum Analyzer. To study the ODMI, the pick-up coil was wound around the microwire. The coil with inner diameter of 2 mm had 100 turns. The dependences of the amplitudes of the first and second harmonics in the pick-up coil voltage on the external field and the value of the bias current were measured. The external magnetic field was varied within the range \pm 20 \text{ Oe}.

3. Results and discussion

The measured hysteresis loops are presented in figure 1. The coercivity obtained by the VSM and inductions methods differed significantly, the VSM method gives the value of the order of 50 mOe, whereas for the induction method the coercivity is about 0.5 Oe. The difference may be explained as follows. The induction method is the dynamic one and in the greater degree characterizes a radial distribution of the longitudinal magnetization in the microwire. A change in the magnetization under action of the longitudinal magnetic field begins from the microwire axis, where the anisotropy has the minimum value. On the other hand, in the dynamic mode the depth of the penetration fields is determined by an effective permeability at the given frequency.

![Figure 1](image1)

**Figure 1.** Magnetization curves measured by means of (a) VSM method and (b) induction method.

The field dependences of the real and imaginary parts of the impedance are shown in figures 2 (a) and 2 (b). Arrows mark the direction of the change in the external magnetic field. The behavior of the impedance correlated with a dynamic loop. However, it follows from figures 2 (a) and 2 (b) that at low fields the hysteresis was absent, that is, the minimum value of the impedance was independent of the direction of the change in the external field. This fact corresponds to the behavior of the VSM loop.

Figure 2 (c) presents the frequency dependence of the peak value of the transverse permeability and the ratio of the skin depth to the microwire radius evaluated from the measured real part of the impedance. Estimations were made by means of the relations \delta / a \approx 1 - (1 - R / R_0)^{1/2}, \mu \approx c^2 \rho / 4 \pi f \delta^2, where \delta is the skin depth, a is the microwire radius, R is the real part of the impedance, R_0 is the dc resistance, \mu is the permeability, c is the velocity of light, \rho is the resistivity and f is the frequency.

The effective permeability for the longitudinal excitation should not differ strongly from that for the transverse excitation, since it reflects the dynamics of the same magnetic moment. The extrapolation of the curves to the low-frequency range shows that the skin effect can be significant even at low frequencies. The induction method characterizes the behavior of the magnetization within a surface.
layer of the microwire, and the cross-section of this layer changes in size with a variation of the longitudinal field. In the induction method, a signal from the pick-up coil is integrated, recovering a magnetization from the measured susceptibility. It is clear that in this case the radial magnetization distribution, which gives the observed hysteresis, is not taken into account. In the VSM method, this disadvantage is absent.

![Figure 2](image)

**Figure 2.** The field dependences of (a) real and (b) imaginary parts of the impedance at the current amplitude of 1 mA and the frequency of 1 MHz. (c) The frequency dependences of the skin depth and the permeability calculated from the real part of the impedance.

![Figure 3](image)

**Figure 3.** The amplitudes of (a) first and (b) second harmonics as a function of the external magnetic field at different bias current $I_b$ and at the current amplitude of 1 mA and the frequency of 1 MHz.

The field dependence of the amplitude of the first harmonic in the pick-up coil voltage is shown in figure 3 (a). At zero bias current, the first harmonic signal was very low. The first harmonic amplitude increases with the bias current. The field dependence of the first harmonic has an asymmetric behavior, with the peak at the positive external field being higher than that at the negative field.

Let us discuss the relationship between the linear ODMI and surface domain structure of the microwire. Magnetic properties of amorphous samples are determined by magnetoelastic interactions. Due to the effect of the internal stresses, the surface layer of Co-based amorphous wires and glass-coated microwires with a negative magnetostriction has a circular or helical anisotropy [1]. It is assumed usually that at low external magnetic field, this layer is subdivided into the domains with oppo-
site magnetization direction (the so-called bamboo domain structure) [7]. However, calculations have shown that the bamboo domain structure is energetically unfavorable for wires with slightly negative magnetostriiction, and the uniform magnetization distribution in the surface layer may exist [8].

The ODMI is sensitive to the surface domain structure, and the pick-up coil voltage attains a maximum in the single-domain wires. In wires with the bamboo domain structure, the contributions to the ODMI from adjacent domains with the opposite circular magnetization direction have different signs. As a result, the ODMI averaged over the domain structure should be very small [4]. It has been demonstrated that the ODMI effect can be used to study the surface structure of Co-based amorphous wires [9,10]. Analysis of experimental results shows that the regular bamboo domain structure does not exist in different Co-based amorphous wires [5,9,10].

The surface magnetic structure in glass-coated microwires is mainly governed by internal stresses induced at the interface between the amorphous core and glass coating due to the difference in the thermal expansion coefficients in the amorphous phase and the glass. These stresses may result in appearance of the bamboo domain structure in Co-based microwires. In particular, this structure has been observed previously by means of magneto-optical methods [11].

The almost zero first harmonic amplitude in the pick-up coil voltage indicates the presence of the bamboo domain structure in the studied microwire. Due to low coercivity of the sample, the application of low bias current leads to the difference in the relative volume of the domains and to the elimination of the bamboo domain structure. As a result, the linear ODMI increases with the bias current.

The measured second harmonic amplitude is shown in figure 3 (b) as a function of the external magnetic field. On the contrary to the first harmonic, the second harmonic differed significantly from zero in the absence of the bias current. With the increase of the bias current, the second harmonic amplitude drops. The appearance of the second harmonic in the pick-up coil voltage at low external field can be ascribed to the domain-walls motion [12]. The oscillations of the domain walls under action of the alternating current result in a change in the relative volume of the domains. Since the direction of domain-walls motion changes twice per the current variation cycle, the second harmonic is the main in the pick-up coil voltage frequency spectrum [12].

Acknowledgment
This work was supported by the Program “Support of Innovations” of Russian Academy of Sciences.

References
[1] Vázquez M and Hernando A 1996 J. Phys. D: Appl. Phys. 29 939
[2] Zhukov A, González J, Vázquez M, Lin Y and Torcuano A 2004 Encyclopedia of Nanoscience and Nanotechnology vol 6, ed H S Nalwa (Stevenson Ranch, CA: American Scientific Publishers) p 365
[3] Knobel M, Vázquez M and Kraus L 2003 Handbook of Magnetic Materials vol 15, ed K H J Buschow (Amsterdam: Elsevier) p 497
[4] Antonov A, Iakubov I and Lagarkov A 1997 IEEE Trans. Magn. 33 3367
[5] Antonov A S, Iakubov I T and Lagarkov A N 1998 J. Magn. Magn. Mater. 187 252
[6] Zhukov A, González J, Blanco J M, García Prieto M J, Pina E and Vázquez M 2000 J. Appl. Phys. 87 1402
[7] Panina L V, Mohri K, Uchiyama T, Noda M and Bushida K 1995 IEEE Trans. Magn. 31 1249
[8] Usos N, Antonov A, Dykhne A and Lagar’kov A 1997 J. Magn. Magn. Mater. 174 127
[9] Rakhmanov A A, Antonov A S, Buznikov N A and Prokoshin A F 2006 J. Magn. Magn. Mater. 300 e37
[10] Samsonova V, Antonov A, Iakubov I, Nastasjuk A, Perov N and Rakhmanov A 2007 J. Non-Cryst. Sol. 353 938
[11] Shalygina E E, Molokanov V V and Komarova M A 2002 JETP 95 511
[12] Buznikov N A, Antonov A S, Kim C G, Kim C O, Rakhmanov A A and Yoon S S 2005 J. Magn. Magn. Mater. 285 101