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SOLID STATE

Influence of Current Annealing on the Temperature Dependences of Magnetoimpedance in Amorphous Microwires

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Abstract—Further miniaturization of magnetic electron devices and devices of microsystem engineering in many ways depends on the optimal choice of functional materials (media) used in working bodies, specifically, sensory elements (for example, in local magnetic field sensors, mechanical stress/strain sensors, temperature sensors, etc.). Among promising materials in this respect are ferromagnetic wires consisting of a glass-coated amorphous alloy filament. The magnetoimpedance of such filaments turns out to be highly sensitive to the above external factors: the so-called giant magnetoimpedance effect. The performance of these devices is highly temperature stable, which is important for many applications.

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INTRODUCTION

In this article, we report the influence of temperature on the magnetoimpedance of amorphous ferromagnetic $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$ microwires. Alloys of this composition have a relatively high Curie point (T_C > 300°C), but the magnetic properties of microwires made of them are often temperature-dependent even near room temperature (below 100°C). To make magnetization processes and magnetoimpedance temperatures stable in a wide temperature interval, microwires were heat treated by passing constant current through them.

The Curie point is an important characteristic of magnetic materials used in advanced microelectronic devices and devices of microsystem engineering as working bodies and/or media. In particular, this parameter to a great extent governs the temperature dependence of most magnetic properties and, consequently, the working temperature range and thermal stability of devices based on these materials. Ferromagnetic alloys of 3*d* metals laced with other elements (diluents and/or amorphizers) that are applied in lower dimension products (thin films, micro- and nanowires) are objects of great interest for many teams of researchers.

Today, amorphous ferromagnetic microwires (AFMs) seem to be most appropriate for use in sensor systems owing to their specific anisotropic behavior [1, 2]. In the presence of mechanical stresses due to the difference between thermal expansion coefficients of the filament and sheath, a stress-induced magnetic anisotropy arises in wires with a near-zero positive or negative magnetostriction constant. Arising magnetic anisotropy may be longitudinal (the easy magnetization axis is aligned with the wire's axis) or of a specific type (circular or helical) [3]. The final magnetic structure of wires governs the magnetization type and dynamics, as well as the shape of the hysteresis loop. In addition, many properties of such wires depend on external factors (mechanical stresses and strains, temperature) [4–6]. Therefore, they can be used as sensitive elements in different sensors [7, 8].

The AFM properties can also be controlled by using different ways of their modification. In a number of papers devoted to AFMs subjected to different heat treatments, it was reported that annealing parameters strongly influence the mechanical performance, magnetization, magnetic anisotropy, magnetostriction, coercive force, Curie point, resistance, and other parameters of microwires [9–16].

Thermal annealing in the presence of a magnetic field, which can be easily applied to an AFM or the entire magneto impedance sensitive element, is of great technical interest in view of improving the sensitivity of the sensor without changing its design. It should be noted here that controlling the properties of microwires by weakening magnetoelastic coupling via the proper selection of an alloy and parameters of subsequent thermal annealing allows one to reach a maximal value of the magnetic impedance (MI): 600% at a frequency of 15 MHz [17].

To know how annealing influences the hysteresis loop, magnetostriction coefficient, and giant magnetoimpedance (GMI) effect in AFMs is essential for gaining insight into processes governing magnetic softness and thereby for improving the magnetic performance of the material (specifically, for enhancing the GMI effect) [18]. On the other hand, the reliable performance of a sensor element is based on the temperature stability of its magnetic properties. Therefore, we studied the influence of annealing parameters on the temperature dependence of magnetic properties of microwires with rated composition $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$. As-prepared microwires of this composition exhibit an extremely low magnetostriction and are considered most promising for applications using the GMI effect.

The magnetic properties depend on temperature, since heating leads to relaxation of process-induced internal stresses, which are undesirable in MI-based sensors. On the other hand, in high-magnetostriction amorphous wires with a low Curie point [19], the temperature dependence of MI can be controlled and used in local ambient temperature measurements. Thus, using alloys of nearly identical chemical compositions, one can produce a wide spectrum of temperature-sensitive microwires by controlling the Curie point from room temperature to ~300°C.

Earlier, it was noted [20] that during current annealing, the microwire not only is heated but also is subjected to the circular magnetic field of the current. The joint action of heat and the magnetic field induces circular magnetic anisotropy, which becomes most pronounced at the periphery of the wire and eventually enhances the GMI effect.

Recently, the influence of such parameters as the frequency, amplitude, and direction of magnetic field on the GMI effect and magnetic performance of cobalt-based microwires during current annealing has been studied [21, 22]. It was found that annealing results in formation of a sophisticated domain structure in microwires. Because of this, we conducted thermal annealing in such a way that annealing parameters and ambient temperature provided a tradeoff between the sensitivity of the GMI effect in wires and thermal stability of the wire's magnetic performance. In the experiments described here, we studied the temperature dependence of the GMI effect in as-prepared and annealed microwires. Annealing was carried out by passing 25-mA constant current through wires for 60 min at low and high frequencies (40 and 300 MHz).

1. DETAILS OF THE EXPERIMENT

The influence of temperature on the GMI effect was studied on glass-coated $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$ amorphous wires 24.7 μm in diameter. The wires were obtained by the Taylor–Ulitovski method [23], and their Curie point was above 300°C.

The wires were processed by 25-mA electrical current applied from a constant-voltage power supply. The current acted on a 15-cm-long microwire for 60 min. During current passage, the microwire was fixed in the properly expanded state using a special holder. The ends of the microwire were attached to the holder using a tin solder.

The MI of wires was determined by measuring parameter S12 in a wide frequency range (1–300 MHz) using an HP 8753E vector network analyzer. A test sample was placed in a dedicated microstrip cell (sample holder). A magnetic field with a strength of ±20 Oe was generated by Helmholtz coils. A measuring unit integrated magnetizing coils with a container, which fixes microstrip cells, and a thermally insulated chamber. The cells were connected to transceiver ports of a network analyzer. A piece of wire 1 cm long was soldered to contact pads of the measuring cell and was excited by a signal from a sine-wave voltage source. The amplitude of alternating excitation current in the wire equaled 2–3 mA. The temperature in the chamber was varied from room temperature to 90°C and was measured by means of a thermocouple.

After processing experimental data, we compared the results of wire impedance measurements before and after current annealing.

2. RESULTS AND DISCUSSION

2.1. Magnetoimpedance Properties of As-Prepared Wires

Figure 1a plots MI Z of the as-prepared microwire versus magnetic field H at a frequency of 40 MHz in the interval from room temperature to 90°C. Up to 70°C, $Z(H)$ curves of the microwires taken both before and after current annealing have two peaks with a dip correlating with absence of a magnetic field. With a rise in temperature, the magnetic sensitivity of the impedance in low magnetic fields considerably drops. Above 70°C, the plots radically change: a single central peak appears near a zero magnetic field (such a bell-shaped form is observed at 80 and 90°C). The change in MI behavior is observed when circular magnetic anisotropy transforms into axial anisotropy because of internal stress relaxation. The immense decrease in the GMI effect with rising temperature at $H = 0$ (more than 200% at 80°C) is unacceptable as far as the application of these wires as magnetosensitive elements in magnetic field sensors is concerned.

Figure 1b shows the influence of temperature on the MI at higher frequencies (to 300 MHz). In this case, a very high sensitivity of the GMI effect and a strong variation of the impedance with temperature (up to 250% at 90°C) are observed; however, heating does not result in a single-peak impedance. Since, at higher frequencies, the subsurface layer of the AFM's

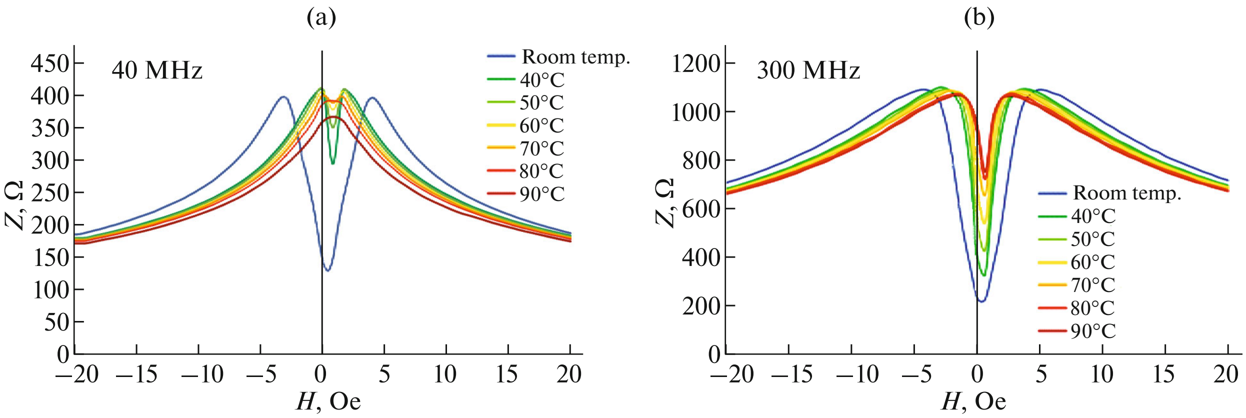

Fig. 1. MI of as-prepared $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$ amorphous wires vs. magnetic field strength for different temperatures at a frequency of (a) 40 and (b) 300 MHz.

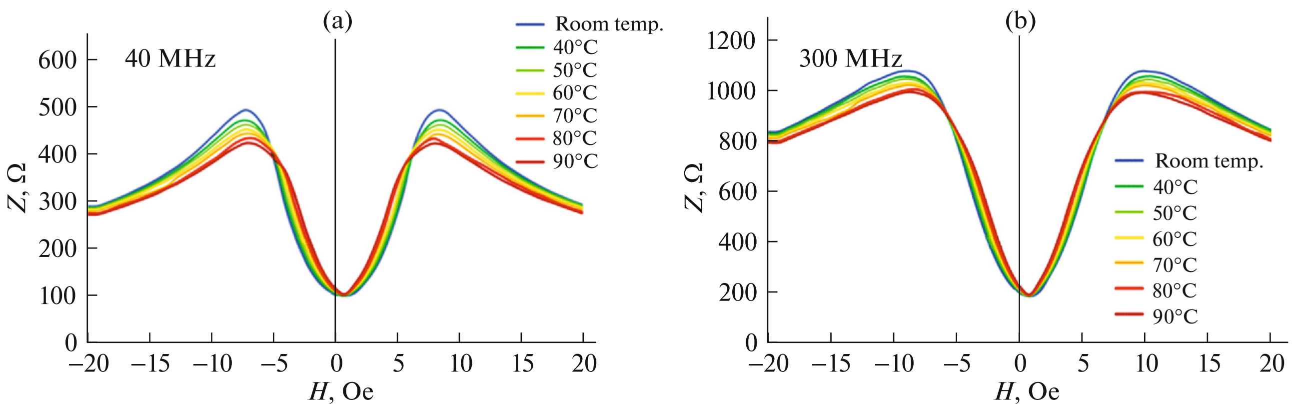

Fig. 2. MI of annealed $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$ amorphous wires vs. magnetic field strength for different temperatures at a frequency of (a) 40 and (b) 300 MHz.

metallic filament makes a contribution to the GMI effect, one can assume that the direction of the easy magnetization axis will persist at still higher temperatures, although the constant of circular/helical anisotropy continuously decreases with increasing temperature. Thus, it is safe to postulate the suitability of the wires of the studied composition for building high-frequency sensor devices, but it is required to ensure the temperature stability of their characteristics.

2.2. Magnetoimpedance Properties of Annealed Wires

The behavior of wires with the GMI (GMI wires) that were subjected to current annealing was studied at different frequencies because of the possibility of inducing circular anisotropy during processing and raising the sensitivity of the GMI. As to the influence of current annealing, it should be noted that the magnetic structure of glass-coated AFMs is such that the central part of the filament with an axially directed magnetization vector is surrounded by near-surface layers with a circular or helical magnetization distribution. In cast wires, the internal region usually occupies a major part of their volume. The surface region with circular anisotropy may be expanded during current annealing by inducing additional anisotropy in the presence of a circular magnetic field of the current through the formation and ordering of magnetoactive atomic pairs.

From magnetic field dependences of the impedance taken at different temperatures (Fig. 2) it follows that dc annealing of AFMs considerably improves the thermostability of the impedance in the frequency range 1–300 MHz. For example, when the field is absent, the AFM impedance is temperature-independent in the interval from room temperature to 90°C. This stability against temperature rise may be associated with the fact that the relaxation of process-related mechanical stresses become maximal as early as current heating and current-induced circular magnetic field enhanced circular anisotropy. Upon annealing, MI peaks shifted from 5 Oe before annealing to 8 Oe after it; accordingly, the interval of maximal sensitivity of the MI to magnetic field variation expanded. However, the sensitivity of the MI at low fields somewhat decreased from 55 to 40% Oe (Fig. 2a, 40 MHz). This is because the maximal value of impedance depends on the distribution of magnetic anisotropy easy axes in the AFM, in which current annealing diminishes the volume of its central part with a primarily axial direction of magnetization.

The same conclusion can be drawn from the behavior of annealed GMI wires at higher frequencies (Fig. 2b). Importantly, the sensitivity considerably rises with frequency (however, here the rise is less significant than for unannealed wires) and the temperature stability is high. Thus, the slight influence of temperature on the GMI does not affect the feasibility of applying microwires in industrial devices that exploit the GMI effect. After current annealing, the sensitivity of the GMI at relatively high frequencies may be significant but thermally stable (throughout the frequency range studied) under normal operating conditions. It is expected that the sensitivity will not strongly depend on environmental conditions at elevated or low temperatures.

CONCLUSIONS

The temperature dependence of MI of glass-coated $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$ amorphous wires was studied before and after dc annealing. Annealing was applied to achieve a trade-off between the sensitivity and thermal stability of the GMI effect. A GMI signal at low and high frequencies in the interval 1–300 MHz demonstrated the rise in sensitivity with rising frequency; however, the influence of heating was most pronounced at high frequencies. Current annealing resulted in formation of clear-cut circular magnetic anisotropy, the influence of heating temperature being insignificant up to 90°C. Such wires will be useful for designing industrial magnetic-field sensors.

It was shown that magnetic anisotropy in microwires noticeably changes from circular to axial because of internal stress relaxation. As a result, the behavior of the MI changes drastically: MI curves with two symmetric peaks transform to curves with a single central peak.

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