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# GMI Effect in Annealed $Fe_{40}Ni_{38}Mo_4B_{18}$ Microwires

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Amorphous glass-coated microwires are ideal material for miniaturized applications for sensing the temperature, stress and magnetic field. One of the key parameters for future applications is their time and thermal stability. It has been shown that stability can be improved by using nanocrystalline materials that combine good soft magnetic properties of amorphous matrix with high structural stability of crystalline grains. Such nanocrystalline materials are usually obtained by annealing of amorphous precursor. In the given contribution, the influence of dc current annealing on the domain structure and GMI effect in amorphous and nanocrystalline $Fe_{40}Ni_{38}Mo_4B_{18}$ magnetic microwire has been studied. The annealing induces additional circular magnetic anisotropy, stress relief and structure homogenization. However, the increase of magnetostriction results in the decrease of GMI. Annealing at optimum crystallisation temperature results in an increase of the relative permeability due to the formation of the nanosized grains. Consequently, GMI amplitude is comparable to that of as-cast state.

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## 1. Introduction

The Giant Magnetoimpedance (GMI) effect consists of a large variation of the impedance $Z$ of a metallic magnetic conductor when submitted to the action of a dc magnetic field $H$. The GMI varies with the frequency. At high frequencies, effect originates from the dependence of skin depth $\delta$ upon the circumferential magnetic permeability of the samples $\mu_\Phi$. In order to obtain large GMI values, it is necessary to reduce skin depth by choosing magnetic materials that have large circumferential permeability. GMI effect, observed in some low magnetostrictive amorphous soft magnetic glass-coated microwires, has been intensively studied due to its great potential for developing high sensitivity magnetic field sensors. The glassy cover of microwires induces large internal stresses in its metallic core. Thus, the magnetic properties of microwires are very sensitive to the magnetostriction constant $\lambda_s$ [1]. Joule heating is a very simple way to reduce this stresses and to induce magnetic anisotropies [2, 3]. The domain structure of such wires consist of an inner core and an outer shell with circumferentialy oriented magnetization. Different kinds of heat treatment can play an important role in modifying the domain structure and hence the GMI values. The nanocrystalline $Fe_{40}Ni_{38}Mo_4B_{18}$ alloy, which exhibits positive magnetostriction, is a new nanocrystalline soft magnetic material. The nanostructured $Fe_{40}Ni_{38}Mo_4B_{18}$ specimens, obtained by annealing of the amorphous alloy in the temperature range from 650 K to 1060 K have the microstructure of a $\gamma$-FeNi crystallites with average grain size 10 nm, embedded in a residual amorphous matrix [4, 5]. In this article we investigate the influence of Joule-heating and crystallization on the GMI effect in $Fe_{40}Ni_{38}Mo_4B_{18}$ wires.

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## 2. Experimental procedure

The wire, with core diameter of 8 $\mu$m and glass cover thickness of 2 $\mu$m, was prepared by Taylor-Ulitovsky technique. The glass-coating was mechanically removed from the sample ends and the electric contacts were attached. The sample of 3.6 cm in length was inserted in a cylindrical coil, wound on a glass tube with an outer diameter of 5 mm. This coil was used to generate the external magnetic field in the range 2000 $\mathrm{A\cdot m^{-1}} \geq H \geq 0$, parallel to the wire axis. The same sample was Joule-heated for 10 min by a constant current from the range between 6 and 22.5 mA. The same sample has been used for all treatments. Impedance $Z$ was measured at room temperature by the four-point method at the frequency of 2 MHz and drive current amplitude of 1 mA using a Tectronix oscilloscope.

## 3. Results and discussion

The crystallization temperature of the amorphous $Fe_{40}Ni_{38}Mo_4B_{18}$ alloy (core of the microwire) was determined by thermal analysis of the electrical resistance $R_{dc}$ (Fig. 1). The structural relaxation processes in the amorphous alloy correlates with the decrease of the resistance in the first stage of thermal treatment ($1 \to 2$). Resistivity starts to increase after heating of the sample at 10 mA ($2 \to 3$) as a consequence of the internal stresses relief and structure homogenization. Upon heating up to temperature $T_{ax} \sim I_{ax} \cong 18.7$ mA, the structure evolves to nanocrystalline, and resistance starts to decrease ($3 \to 4$). The optimal current for nanocrystalline structure formation is 19 mA. Heating at higher currents induces new internal stresses which are much stronger than that from the amorphous wire and resistance increases ($4 \to 5$). Because of higher temperature coefficient of the resistance of the crystalline phase the cooling part of $R_{dc}(I_a)$ dependence has a steeper slope $(5 \rightarrow 6)$.

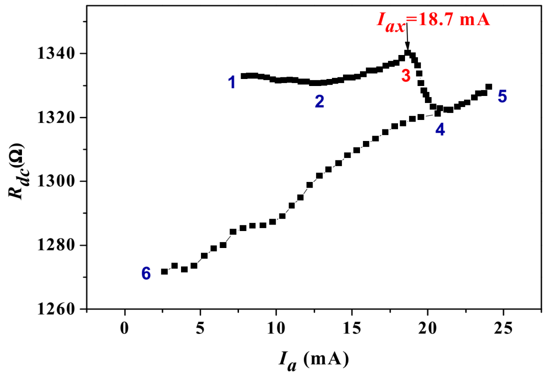


Fig. 1. Influence of the annealing current on the resistance $R_{dc}$.

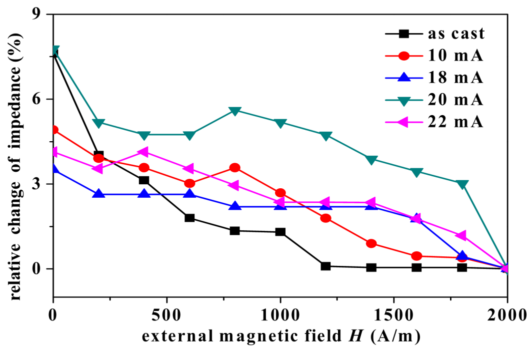


Fig. 2. Relative impedance $\Delta Z/Z(H)$ of microwire after Joule-heating from 0 to 22 mA.

Relative impedance measured at frequency of 2 MHz with dc external magnetic field $H$ applied along the wire axis is shown in Fig. 2. The relative change in GMI with applied magnetic field was calculated using the expression:

$$\frac{\Delta Z}{Z}(\%) = 100 \times \left( \frac{Z(H) - Z(H_{\max})}{Z(H_{\max})} \right), \qquad (1)$$

where $H_{max} = 2000$ A/m.

Strong stresses (mainly axial and radial) are introduced during the microwire production, leading to small values of magnetic permeability. Hence, the relative impedance $\Delta Z/Z$ for the as cast wire is small, and decreases rapidly, achieving maximum value of about 7.60%. After annealing at low dc current (at low temperatures), the stresses magnitude decreases and the easy axis becomes parallel to the wire's axis. Moreover, the magnetostriction constant $\lambda_s$ of amorphous $Fe_{40}Ni_{38}Mo_4B_{18}$ alloy increases [6], leading to the decrease of circular magnetic permeability. As a result, the maximum of $\Delta Z/Z$ ratio is smaller (4.91% at $I_a = 10$ mA and 3.51% at $I_a = 18$ mA , respectively). Nanocrystallization, after the Joule-heating over $I_{ax} = 18.7$ mA (not shown in fig. 2), has resulted in a small increase of relative impedance but its values of 7.38% ($I_a = 19$ mA) and 7.77% ($I_a = 20$ mA) are comparable with those of the as cast microwire. This effect can be related to the magnetostriction constant $\lambda_s$, which decreases in the first stage of the crystallization. The magnetostriction of the nanocrystalline $Fe_{40}Ni_{38}Mo_4B_{18}$ alloy $\lambda_{sn}$ consists of two parts: one is the $\lambda_s$ of the crystalline phase $\lambda_{sc}$ and the other is the $\lambda_s$ of residual amorphous phase $\lambda_{sr}$. At $T_a = 750$ K [6], the mass fraction of the crystallized part increases to 65%, and the average magnetostriction is $\lambda_{sn} \sim 10.5 \times 10^{-6}$, which is comparable with the magnetostriction value of the amorphous $Fe_{40}Ni_{38}Mo_4B_{18}$ alloy $\lambda_s = 11 \times 10^{-6}$. This is the reason why the alloy does not shown a higher permeability after nanocrystallization, as it is in the case of Finemet, where the $\lambda_{sn} \sim 0$ after nanocrystallization [7]. Since the nanostructured material exhibits homogenous nanostructure and uniform stresses distribution, the dependence $\Delta Z/Z = f(I_a)$ for nanocrystalline microwires decreases slower than for the as-cast wire. After annealing at higher currents, $I_a > 20$ mA, the material of microwire becomes fully crystalline and relative variation of the impedance decreases.

## 4. Conclusions

The variations in GMI value indicate on structural transformation and modification of magnetic behavior in $Fe_{40}Ni_{38}Mo_4B_{18}$ alloy during thermal treatment.

The annealing at $I_a < I_{ax}$ gives rise to a stress relief in the amorphous alloy and leads to the decreas of the relative impedance $\Delta Z/Z$. Probably, the high value of the magnetostriction constant $\lambda_{sn}$ is the reason for the low GMI value after nanocrystallisation.


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