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THIN MAGNETIC AMORPHOUS WIRES FOR GMI SENSOR

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This paper presents a study of the GMI in amorphous conventional wires with nearly zero magnetostriction ($Co_{68.18}Fe_{4.32}Si_{12.5}B_{15}$) having different diameters obtained by cold drawing processes in multiple steps. The purpose of our work is to find the way in which the sensitivity of GMI effect is affected by the decrease of the wires diameter and also the way in which the stress induced during the cold drawing process influence the configuration of the magnetic domains structure through the modification of the magnetoelastic energy. We have performed a study of the giant magneto-impedance effect (GMI) in nearly zero magnetostrictive conventional amorphous wires with diameters between 150-20 μm. The values of the impedance (Z) and GMI ratio (ΔZ/Z) were measured in the frequency range 100 kHz – 10 MHz for wires in the as cast state and cold drawn. We obtained a GMI ratio four times higher for cold drawn wires with diameters of 20 – 30 μm subjected to thermo-mechanical treatments in comparison with the as cast wire of 130 μm diameter. The results are discussed considering the correlation between induced stresses and modifications in circumferential magnetic domains configuration.

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1. Introduction

The GMI effect consisting of a significant change in the impedance of a soft magnetic material placed in a static magnetic field and driven by a high frequency current, arises mainly from the changes in the dynamic magnetization processes as the frequency of the driving ac current increases. Such changes (damping of domain wall motions, changes in the mode in which the magnetization proceeds in a given direction) affect the magnetic permeability and consequently~~,~~ the magnetic penetration depth of the ac current through a magnetic conductor at high frequencies [1~~,~~2]. Magnetic amorphous wires with nearly zero magnetostriction show high sensitivity of the GMI effect, being promising for magnetic sensors applications. The GMI effect sensitivity in amorphous wires depends mainly on the wire composition, which is responsible for the magnetostriction constant but also on the mechanical stresses induced by the fabrication process. The stress distribution determines the value of the circumferential magnetic anisotropy constant and the value of the magnetic permeability at the wire surface. The development of the new sensitive sensors based on the GMI effect requires high GMI effect sensitivity at low external magnetic field.

The aim of our work is to study the GMI effect sensitivity dependence on the wire diameter and on the thermo-mechanical treatments.

2. Experimental

Amorphous wires with diameters between 150-70 μm and nominal composition $Co_{68.18}Fe_{4.32}Si_{12.5}B_{15}$, were obtained by rotating-water rapid quenching from the melt and also by cold

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drawing in multiple steps from 130 μm down to 20 μm. The samples were subjected to heat treatments at 200 – 300 ^{0}C by annealing in a conventional furnace in vacuum using a set heating rate and by passing a current through the sample (Joule effect). Also mechanical treatments (consisting of applied stress) were performed for some samples during the annealing process. The magnetic characteristics of the amorphous wires in the as cast state, after cold drawing in multiple steps process and also after heat treatments were studied. The hysteresis loops both for axial and circumferential excitation field were traced and compared, the latter being related to the circular magnetization process as the effect of a circular magnetic field, produced by an AC driving current. The other parameter determining GMI is the working frequency. Depending on the frequency, three main regions can be defined: a) at low frequencies, the change of the impedance is exclusively ascribed to the magneto-inductive effect arising from the circular magnetization process; b) at around 100 kHz and above, the skin effect is significant because of the large permeability and c) typically above 15 MHz, domain walls motion is fully damped and the permeability strongly decreases until the resonance phenomena are reached. In the case of the two first frequency ranges, the impedance (Z) is measured by the so-called four point method by which a given AC current flows along the magnetic conductor and a voltage is picked up at its ends. The AC circular field, H_Φ, generated by the current gives rise to changes in the circular component of the magnetization, M_Φ.
We performed impedance (Z) measurements in the frequency range 100 kHz-10 MHz for samples in the as cast state, with diameters between 90 – 150 μm and for samples obtained by cold drawing process as a function of the applied magnetic field, H_{dc}. For the latter special mechanical treatments were performed in order to improve the surface quality of the wires.

3. Results and discussion

The dependence of the impedance (Z) as a function of the applied magnetic field, H_{dc}, for the amorphous wires in the as cast state, with diameters between 70 – 150 μm, is represented in Fig. 1. As it can be seen in Fig. 1 there is a variation in the impedance value with the applied field for all diameters, but the most significant modification for low dc applied magnetic field is for thinner wires. More over, by decreasing the wire diameter in multiple steps cold drawing processes and after adequate heat and surface mechanical treatments, we obtained a higher GMI ratio, $\Delta Z/Z(\%)$, defined as $\Delta Z/Z=(Z(H_{dc})-Z(H_{dc}=0))/Z(H_{dc}=0)$, for the 30 μm wire, as shown in Fig. 2. Such a behavior can be explained by taking into consideration the internal tensile stresses induced by cold drawing process, which determines the modification in the magnetoelastic energy and causes an increase of the outer shell thickness (zone near to the surface of the wire having circumferential magnetic anisotropy) [3,4].

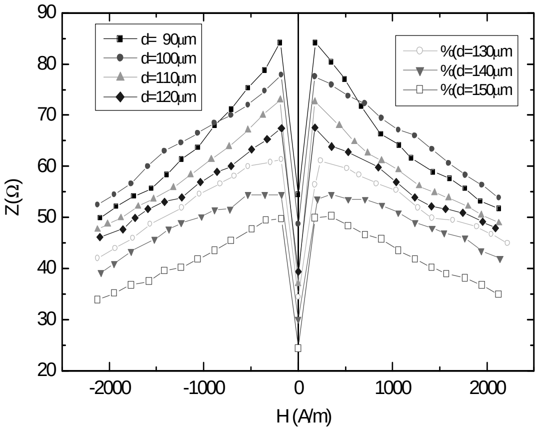


Fig. 1. The impedance at 10 MHz as a function of dc applied magnetic field for $Co_{68.18}Fe_{4.32}Si_{12.5}B_{15}$ amorphous wires in the as cast state.

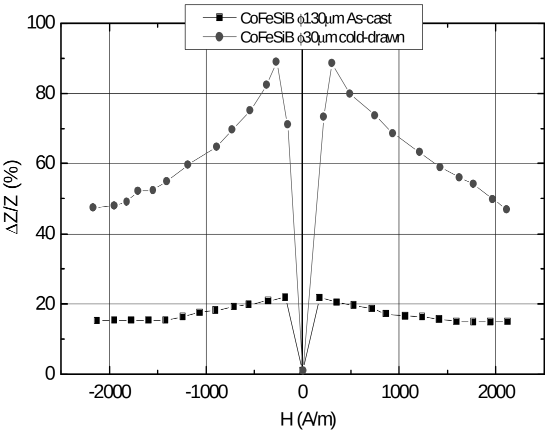


Fig. 2. Field dependence of the GMI ratio for the as-cast and cold drawn wires.

Due to the induced circumferential stresses, the circumferential magnetic anisotropy constant increases and determines an increase of the GMI ratio for low DC applied magnetic fields [5].

The increase of the outer shell thickness with the decrease of the wire diameter through a cold drawing process is confirmed by the circumferential hysteresis loops presented in Fig. 3. At low applied circumferential magnetic fields the value of the circumferential magnetic moment increases with the decrease of the wire diameter. The value of the coercive force in the case of circumferential magnetization process is about five times lower than that measured for longitudinal magnetization process.

Figs. 4(a-c). ilustrate the axial dc field dependence of the impedance as a function of cold drawn wires diameter, at a frequency of 5 MHz. One can also observe a very small increase of the impedance Z with the applied dc field. This behavior confirms the damping of the domain wall motion and shows that the magnetization proceeds in the circumferential direction through a rotation of the magnetic moment. Thus, there is a slight increase of the circumferential permeability at small values of the dc field, the rotations being favored by this field and a corresponding slight decrease of the magnetic penetration depth which leads to the small increase of Z. At higher axial fields even the rotational permeability is depreciated, this determining the decrease of Z.

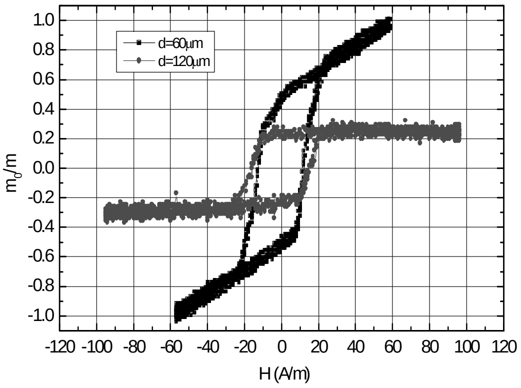
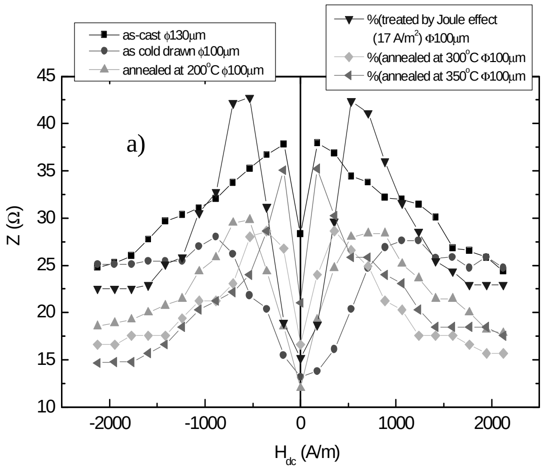


Fig. 3. Reduced circumferential magnetic moment for cold drawn amorphous wires.



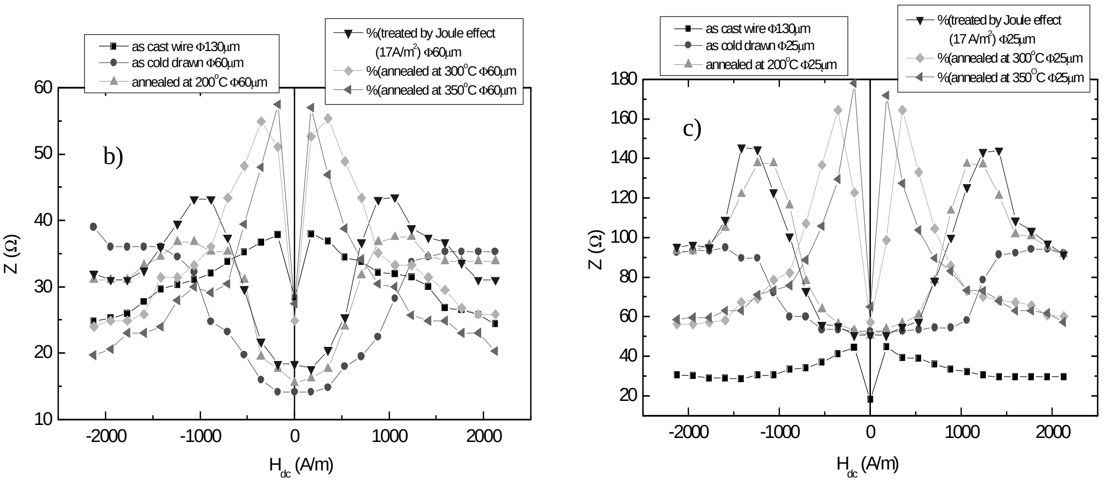


Fig. 4. The impedance dependence on the axial dc applied magnetic field and on the various thermal treatments for three different wires cold drawn in several steps: a) 100μm; b) 60 μm; c) 25 μm.

As it can be seen in Figs. 4(a-c) for the as cold drawn wires, the impedance presents a moderate increase with applied dc magnetic field reaching a maximum at relatively large values of the dc applied field (about 1000 A/m). The value of the dc applied field corresponding to the maximum of the impedance becomes larger since the diameter of the as cold-drawn wire decreases. Such a behavior can be explained taking into consideration the influence of the internal stresses induced by the cold-drawing process on the magnetic domains configuration and consequently on the dynamic magnetization process. The coupling between large internal stresses induced by the cold-drawing process and magnetostriction produces an increase of the magnetoelastic energy. Due to this fact, the magnetic domain configuration in these wires will be one consisting of a core radially magnetized and an outer shell magnetized in a circumferential direction (in conformity with existing models [1,2]). The influence of the internal stresses induced by the cold-drawing process becomes predominant since the as-drawn wires diameter decrease down to 25 μm as it can be seen in the Figs. 4 (a-c). After adequate thermal treatments (the appropriate thermal treatment in our case was the annealing at 350 ^{0}C for 30 minutes), the wires undergo a stress relaxation process that determines a reorganization of the domains structure. The resulting magnetic domain configuration consists of a core axially magnetized and an outer shell which occupies almost the whole volume of the wire. The magnetoelastic anisotropy constant is lower in this case in comparison with that obtained in the as-drawn amorphous wires.

The improvement of the wire surface quality causes modification of the GMI ratio in the range of low dc applied magnetic field.

A controlled reduction of the wires diameter produces a significant increase in GMI ratio in the range of low applied dc magnetic fields making this kind of amorphous wires useful in development of new magnetic sensors based on GMI effect.

4. Conclusions

A controlled reduction of the wires diameter produces a significant increase in GMI ratio in the range of low applied dc magnetic fields making this kind of amorphous wires useful in development of new magnetic sensors based on GMI effect.

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