

## Magneto-Impedance Effect in Amorphous and Nanocrystalline Glass-Covered Wires

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**Abstract**—We report results on the magneto-impedance effect in  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  nanocrystalline glass-covered wires,  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  amorphous wires, and in such wires after glass removal. The results are compared with those obtained for cold drawn and then tension annealed  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  amorphous wires. The magneto-impedance response of nanocrystalline wires after glass removal is larger than that of  $\text{CoFeSiB}$  amorphous wires after glass removal, being almost equal to that of cold drawn  $\text{CoFeSiB}$  amorphous wires. The results are explained in terms of specific domain structures and magnetic properties of the discussed wires, and they reveal the importance of good soft magnetic properties in a large magneto-impedance effect.

**Key words:** magneto-impedance effect, amorphous glass-covered wire, nanocrystalline glass-covered wire, soft magnetic material, nearly-zero magnetostrictive material

### 1. Introduction

The magneto-impedance (MI) effect, that consists of a variation of the high frequency impedance of a magnetic conductor subjected to a dc magnetic field, has been widely studied recently, and it was found appropriate for microsensor applications<sup>1)</sup>. The most sensitive MI effect was reported in  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  amorphous wires with diameters reduced down to 30  $\mu\text{m}$  by cold drawing in several steps, which were subsequently tension annealed in order to induce a circumferential domain structure in their entire volume. The impedance behavior depends on the wire's static magnetic properties, and on the dynamics of magnetization in the circumferential direction, that influences the magnitude of the skin effect.

The aim of this paper is to perform a comparative study of the MI effect in  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  amorphous glass-covered wires (AGCW) and  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  nanocrystalline glass-covered wires (NGCW), and in  $\text{CoFeSiB}$  amorphous wires after glass removal (AWAGR) and nanocrystalline wires after glass removal (NWAGR). We have chosen these materials since the AGCW and AWAGR display a circumferential domain structure in their surface layer, favorable for a large MI effect, while the NGCW and NWAGR display very good soft magnetic properties, this feature being also important for a large MI response. The results are compared with those obtained for  $\text{CoFeSiB}$  cold drawn amorphous wires (CDAW).

These results offer information about the importance of good soft magnetic properties with respect to that of an appropriate domain structure, in a large MI effect, and

offer an important guideline with regard to the choice of an optimum material for an MI-based application.

### 2. Experiment

We prepared  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  and  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  amorphous glass-covered wires (AGCW) by glass-coated melt spinning. For the experimental investigations we selected samples with the metallic core diameter of 15  $\mu\text{m}$  and the glass cover thickness of 5  $\mu\text{m}$ . The amorphous state was checked by X-ray diffraction. The  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  amorphous samples, both glass-covered and those obtained after glass removal, were annealed in vacuum for 1 h, at temperatures up to 600°C. Each annealing step was performed starting from the as-cast amorphous state. Cold drawn  $\text{CoFeSiB}$  amorphous samples with 30  $\mu\text{m}$  in diameter, made by Unitika Ltd. R&D Center, have been kindly supplied by Prof. Kaneo Mohri, the Nagoya University, Japan.

MI measurements were performed on 4 cm long samples using a digital oscilloscope coupled to a computer, at frequencies of the ac driving current up to 10 MHz, its amplitude being kept constant at 15 mA, in order to avoid its influence on the MI effect, but to study only the influence of frequency and axially applied dc field. The maximum value of the dc field was  $H_{dc}^{max} = 1\text{ kA}\cdot\text{m}^{-1}$ .

### 3. Results and discussion

In order to analyze the magnitude of the MI effect in the above mentioned materials, we used the reduced impedance change ratio, usually called the MI ratio, defined as:

$$\Delta Z/Z = [Z(H_{dc} = 0) - Z(H_{dc}^{max})]/Z(H_{dc} = 0) \quad (1)$$

in which  $Z$  is the impedance and  $H_{dc}$  is the applied dc magnetic field. Different authors defined the MI ratio in different ways<sup>2)-4)</sup>, and consequently, a unitary comparison basis for the results reported in previous works is still missing.

The MI ratio defined according to Eq. (1), contains information about the magnitude of the MI effect, since it relates  $Z$  at no applied field, where its behavior is affected by the frequency of the ac driving current,  $f$ , through the skin effect, and through the changes in the circumferential magnetization processes as well, with  $Z$  at  $H_{dc}^{max}$ , that is a value of  $H_{dc}$  chosen in order to saturate the sample on the axial direction, and thus to damp the circumferential magnetization processes that occur due to the alternating circumferential field generated by the ac driving current.

The dynamics of magnetization in the circumferential direction – domain wall movements or spin rotations – has a decisive role on the magnitude of the MI effect, since it affects the magnitude of the skin effect, through the circumferential permeability,  $\mu_\theta$ , according to:

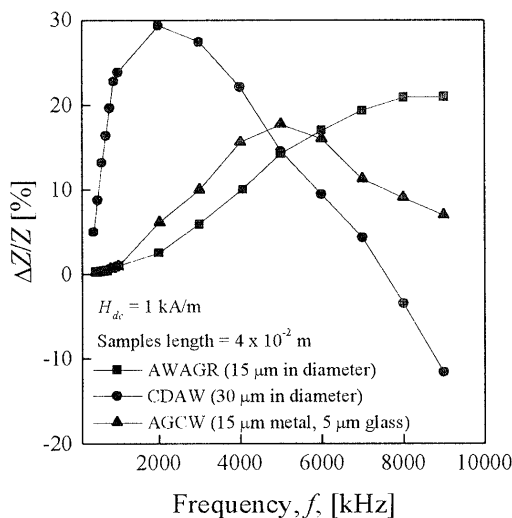
$$\delta_m = (\rho/\pi f \mu_\theta)^{1/2} \quad (2)$$

where  $\rho$  is the wire resistivity and  $\delta_m$  is the flux penetration depth.

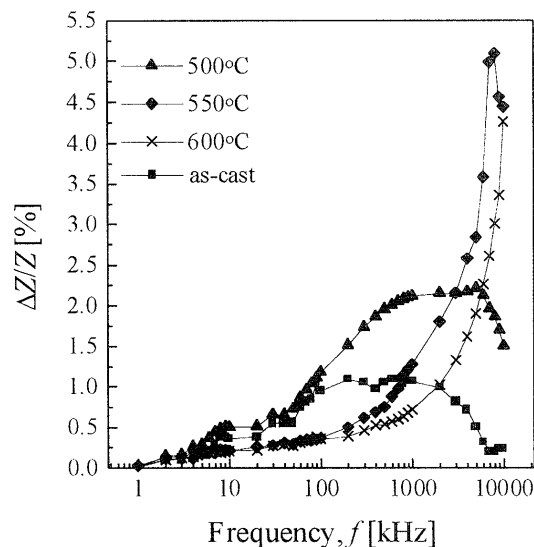
Figure 1 shows the frequency dependence of the MI ratio  $\Delta Z/Z$  for a CoFeSiB AGCW, for the same wire after glass removal (AWAGR), and for a CoFeSiB CDAW.

One observes that the CDAW presents the largest MI effect up to  $f \approx 5$  MHz. For  $5 \leq f \leq 6$  MHz, the AGCW has the largest MI response, while for  $f > 6$  MHz, the AWAGR displays the largest MI effect. It was expected to have a larger effect in the CDAW at the beginning of the frequency range, since the skin effect appears at lower frequencies in this wire, due to its larger diameter. Thus, the circumferential permeability, which is related to the domain wall movements within the surface layer, rapidly drops when the sample is subjected to the dc field, resulting in a large MI effect.

In the frequency range from 5 to 6 MHz, the AGCW displays the largest MI effect, due to its larger rotational permeability,  $\mu_\theta$ , arising from its specific domain structure, that consists of a radially magnetized inner core, and a circumferentially magnetized outer shell<sup>5), 6)</sup>. The rotational permeability of these wires, associated to the circumferential magnetization process that is mainly achieved through spin rotations at these high frequencies, arises both from a part of the radially magnetized inner core and from the circumferentially magnetized outer shell. In this frequency range, the contribution of the radially magnetized inner core fraction is important, this being an unstable state that is easily affected by external factors like  $H_{dc}$ , while  $\mu_\theta$  for the CDAW only drops at similar frequencies.



**Fig. 1** Frequency dependence of the MI ratio for CoFeSiB amorphous glass-covered wires, wires after glass removal, and cold drawn amorphous wires.



**Fig. 2** Frequency dependence of the magneto-impedance ratio,  $\Delta Z/Z$ , for glass-covered FeCuNbSiB wires, with the annealing temperature as a parameter.

For  $f > 6$  MHz, the largest MI response is given by the AWAGR, since its rotational permeability  $\mu_\theta$  is larger at these high frequencies, where the magnetization process is mainly achieved through spin rotations, than that of AGCW, due to its lower circumferential anisotropy originating in the stress relief determined by glass removal. It is important to mention that over 6 MHz, due to the strong skin effect, it is plausible to state that the ac current is passing only through the circumferentially magnetized outer shell, and the axially magnetized inner core of these wires<sup>5), 6)</sup> is not involved in the circumferential magnetization process.

Figure 2 illustrates the frequency dependence of  $\Delta Z/Z$  for differently annealed FeCuNbSiB glass-covered wires.

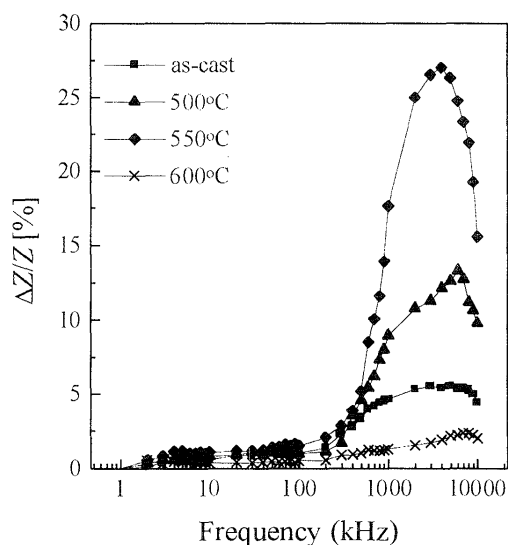
One observes that as-cast FeCuNbSiB AGCW display an MI effect with a maximum MI ratio of 1%. This very small value of  $\Delta Z/Z$  is due to the high positive magnetostriction of FeCuNbSiB AGCW ( $\lambda \approx 25 \times 10^{-6}$ ), that leads through the magnetomechanical coupling with internal stresses to a domain structure with axially magnetized inner core and radially magnetized outer shell<sup>7)</sup>, very unfavorable for the appearance of a large MI effect. After annealing at 500°C, such wires become magnetically softer due to stress relief, and the maximum MI ratio increases to about 2%. After annealing for 1 h at 550°C, the nanocrystalline phase appears<sup>7)</sup> (NGCW), and consequently the wires become magnetically softer, the maximum MI ratio increasing to more than 5%. Annealing over 550°C, leads to a dimensional increase of the  $\alpha$ -FeSi crystalline grains, and consequently, the soft magnetic properties suffer deterioration, resulting in a decrease of the maximum MI ratio to less than 4.5%.

Figure 3 shows the frequency dependence of the MI ratio,  $\Delta Z/Z$ , for differently annealed FeCuNbSiB wires after glass removal. One observes that FeCuNbSiB AWAGR display a maximum MI ratio of 5%.

This behavior is determined by the stress relief produced by glass removal. After annealing at 500°C, the maximum MI ratio increases to about 14%, due to further stress relief. Once the nanocrystalline phase appears (annealing at 550°C), the maximum MI ratio reaches about 28% (NWAGR). Annealing over 550°C results in a deterioration of the good soft magnetic properties, due to the increase in size of the crystalline grains.

NWAGR have a larger MI response as compared to NGCW, since they are magnetically softer (the coercive force is about  $100 \text{ A}\cdot\text{m}^{-1}$  for the first ones, and almost  $400 \text{ A}\cdot\text{m}^{-1}$  for the latter). The MI response of NWAGR is even better than that of CoFeSiB AWAGR, their maximum MI ratio being of about 20%. In addition, the maximum MI ratio of NWAGR is obtained at lower frequencies ( $\sim 4 \text{ MHz}$ ) as compared to CoFeSiB AWAGR ( $\sim 9 \text{ MHz}$ ).

Both these aspects can be explained by considering that at high frequencies, where circumferential magnetization is achieved by spin rotations, the differences in the soft magnetic properties from the outer shells of the two materials play an essential role. Thus, in CoFeSiB AWAGR, a larger energy provided by the circumferential ac field is required in order to rotate the magnetic moments from the easy axis direction toward any other direction, since in this case, the circumferential magnetoelastic anisotropy from the outer shell, determined by the coupling between magnetostriction and large compressive circumferential stresses, is important<sup>6)</sup>. However, changes in the associated circumferential permeability also lead to changes in the value of the penetration depth, although small values of  $\mu_\theta$  are expected. On the other hand, NWAGR are magnetically softer due to their vanishing magnetostriction<sup>7)</sup>. Thus, a larger  $\mu_\theta$  of NWAGR, as compared to CoFeSiB AWAGR, is expected. This fact results in a shift toward lower values of the frequency where maximum MI ratio is detected in NWAGR, and in a larger effect in this case.



**Fig. 3** Frequency dependence of the MI ratio for FeCuNbSiB wires after glass removal, with the annealing temperature as a parameter.

Under these circumstances, we can state that good soft magnetic properties are essential in obtaining a large MI response of a given material. Furthermore, the presence of good soft magnetic properties may be considered as a second criterion in the choice of an appropriate material for an MI-based application, together with the already widely accepted criterion that requires an appropriate domain structure – e.g., circumferential for wires, and transverse for ribbons and thin films.

This statement is well supported by the fact that in the discussed frequency range, the sensitivity of the MI response of NWAGR is very close to that of CoFeSiB CDAW. The tendency of these thin wires (15  $\mu\text{m}$  in diameter) to reach a similar magnitude of the MI effect ( $\sim 28 - 30\%$ ) like the CDAW (30  $\mu\text{m}$  in diameter), emphasizes once again the close relationship between good soft magnetic properties and a large MI effect, since at close values of the resistivities, it is obvious that the differences in  $\mu_\theta$  play an important role in the magnitude of the skin effect.

#### 4. Conclusion

We investigated the MI effect in  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  amorphous glass-covered wires and  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  nanocrystalline glass-covered wires, as well as in such wires after glass removal. The results are compared with those obtained for cold drawn  $\text{Co}_{68.15}\text{Fe}_{4.35}\text{Si}_{12.5}\text{B}_{15}$  amorphous wires. Cold drawn amorphous wires and nanocrystalline wires without glass display the largest MI response. The results are explained by considering the changes in the magnetization processes as the frequency increases, the changes in the magnetic properties determined by glass removal, as well as the structural changes that occur during annealing in the FeCuNbSiB wires. The obtained results indicate the importance of good soft magnetic properties in a large MI response, showing that the existence of very good soft magnetic properties can compensate for the absence of an appropriate domain structure. Our study is important as regards the selection of a proper material for the achievement of MI-based magnetic sensors.

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