Comparative study of magnetic and magnetoimpedance properties of CoFeSiB-based amorphous ribbons of the same geometry with Mo or W additions

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Abstract
Amorphous ribbons with the following compositions Co68.5Fe4.0Si15.0B12.5, Co68.6Fe3.9Mo3.0Si12.0B12.5, Co68.6Fe3.9Mo3.0Si12.0B12.5, and the same geometry were prepared by melt spinning technique despite the technological difficulties usually related to the fabrication of the tungsten containing rapidly quenched materials. The structure, magnetic properties and giant magnetoimpedance effect (GMI) measured in 0.1–100 MHz frequency range were comparatively analyzed. All of the ribbons showed soft magnetic properties but different magnetostriction coefficients, Curie temperatures, saturation magnetizations and GMI features. Both Co65.9Fe3.5W3.1Si16.5B11.0 and Co64.3Fe3.5W4.7Si16.5B11.0 ribbons showed reasonably high Curie temperature above 200 °C suitable for possible applications. Despite very small composition differences of the tungsten containing ribbons, their GMI responses were distinct due to the difference of the effective magnetostriction coefficient evaluated from the shape of the hysteresis loops measured under stress. The Co68.6Fe3.9Mo3.0Si12.0B12.5 ribbon showed the best corrosion stability and the maximum MI of 320% at 15 MHz frequency. For sensor applications, Co64.3Fe3.5W4.7-Si16.5B11.0 ribbons are eligible for frequency interval above 6 MHz.

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1. Introduction
Amorphous alloys or glassy metals (GM) can be prepared by different techniques: electrodeposition, chemical deposition, vapor deposition including ion sputtering, or rapid cooling from the melt. Rapid quenching has become a widely spread method because it is fast, applicable to a wide range of compositions, insures very low contamination level, and it is adaptable to large-scale production [1]. Rapid quenching of molten alloys preserves the amorphous structure of a liquid in a frozen state. The ferromagnetic amorphous alloys containing a large concentration of Fe or Co generally show excellent soft magnetic properties, equivalent or superior to the conventional crystalline soft magnetic materials [2]. In many cases their magnetic properties are comparable with magnetic properties of the best nanocrystalline materials [3,4].

Transition metals (TM) Fe, Co, and Ni and their combinations determine the magnetic properties of (GM). Many other TM (Ti, V, Nb, Ta, Cr, Mo, Mn, Pd, or Al) have also been researched in order to get the best properties for particular conditions. The aim of adding refractory metals (Nb, Mo, Ta, W, Zr) into an amorphous matrix is to impede the Fe-Si grain growth and to block the formation of crystalline boride phases [5]. It was shown that Mo or Cr additions in the Fe- and Co-based alloys prevent the formation of oxides during annealing at high temperatures and increase the corrosion stability [5–7]. The metalloids (M) Si and B are necessary for glass formation in order to stabilize the amorphous structure [8]. One of the important parameters of soft magnetic materials for sensor applications is the stability of their response in a temperature range of −40 to 200 °C [9]. From this point of view, the addition of
elements with very high melting points (Mo, Ta and W) is of special interest. There have been many studies of amorphous ribbons with Mo additions [10,11] but reports on materials with W additions have been very few [5].

Amorphous ribbons of different composition were widely studied as appropriate materials showing very high giant magnetoimpedance effect (GMI). The magnetoimpedance phenomenon consists in a large change of the total impedance of a ferromagnetic conductor, Z, affecting both its real (R) and imaginary (X) components, when submitted to a static magnetic field, H [12,13]. The change in the impedance per unit applied magnetic field is called the MI sensitivity to the magnetic field. The high sensitivity of GMI to an external magnetic field is the basis for using GMI-sensitive elements in sensor applications [14,15]. According to the theory, a large GMI effect should exist in a magnetic material with low resistivity; well-defined magnetic anisotropy with low dispersion of the local anisotropy axes; high magnetic permeability; high saturation magnetization and low damping parameter [16–18]. The Co-based ribbons with nearly zero but negative magnetostriction were found to show the largest GMI ratio [16,19]. These are materials that show an interesting behavior near the Curie temperature [20].

GMI studies have different objectives. Many researches are focused on understanding the GMI mechanisms, interconnections between structural features, magnetic properties and GMI. Other studies are related to applications and are focused on the improvement of magnetic properties of particular materials for exact practical purposes. The study of GMI in amorphous ribbons continues to attract interest due to its importance for both fundamental problems of magnetism and possible applications.

The GMI value depends on multiple essential parameters, including sample geometry [18]. In an amorphous ribbon (homogeneous magnetic sample), the GMI phenomenon is explained as a consequence of the skin effect: the increase of the effective magnetic permeability (1+Δμ) leads to a decrease of the classic skin penetration depth and an increase of the impedance. According to the expression for the penetration depth (δ) one can write [16]:

$$\delta = \frac{1}{fσμ_0}\left(\frac{H_f}{H_m}\right)^{1/2}$$  \hspace{1cm} (1)

where σ is the electrical conductivity and μ is transverse dynamic magnetic permeability. In magnetic materials, the application of a magnetic field changes the magnetic permeability, skin depth, the total value of impedance: Z = Z(δHm). Although there have been many studies of GMI behavior in amorphous ribbons, the accuracy of the measurements of GMI has been significantly improved in recent years and the progress in the instrumentation allowed more precise comparison of the effect of different ribbon compositions and geometrical parameters. Such an improvement offered the possibility of obtaining enhanced accuracy experimental data sets and proving the validity of the models [18,19,21].

In this work, the magnetic properties and MI effect were studied for precise comparative analysis of the properties of Co68.5Fe3.5W3.5Si16.8B11.0 (SW1) and Co64.3Fe2.5W4.7Si16.8B11.0 (SW2) prepared by rapid quenching technique. As a first step, the pure elements (Fe, W, Co, Mo, B, Si ≥ 99.5%) underwent induction alloying in an argon atmosphere. From the master alloy ingots, amorphous ribbon samples of about 25 μm thickness and 0.7 mm width were produced by melt spinning at tangential velocity of ~30 m/s. The molten metal was ejected by argon gas at an over-pressure of 250 mbar through the orifice in the quartz nozzle positioned at -0.2 mm from the wheel surface.

The phase structure of the ribbons was characterized by X-ray diffraction (XRD) using PANalytical X’Pert PRO X-ray Diffractometer with the Cu-Kα radiation (wave length λ = 1.5418 Å). X-ray fluorescence (XRF, Fischerscope x-ray system XDL-B) was used to confirm the element composition of the ribbons in as-prepared state because the ingot compositions can be different from the ribbon compositions especially in the case of the elements with very high melting point. The surface roughness of the ribbons was evaluated by scanning electron microscopy (SEM) using observations from both sides of the ribbon by TM3000 HITACHI in the secondary electrons mode.

The saturation of magnetostriction coefficient (λs), was estimated by measuring the ribbon hysteresis loops under different mechanical stresses using the inductive method. The measuring frequency was 1.7 Hz, an external magnetic field was created by a pair of Helmholtz coils. The applied mechanical stress variation was caused by the variation of the mass (from 0 to 950 g) of the load connected to one end of the ribbon. The magnetostriction coefficient can be calculated from the slope of anisotropy field vs. mechanical stress curve [22].

A vibrating sample magnetometer (VSM, Lake Shore 7404) and a conventional inductive technique were used to study the magnetic properties of the ribbons at room temperature. The inductive hysteresis loops were measured by applying a uniform external magnetic field in plane of the ribbons of 18 mm length (the same length was used for GMI measurements). For the studies of temperature behavior, magnetization vs. temperature (M vs. T) curves were measured by VSM in the temperature range from room temperature to 400 °C.

The magnetoimpedance effect was measured for the 18 mm length ribbons using a longitudinal configuration in which the alternating driving current flowed parallel to the external magnetic

2. Experimental procedure

Amorphous ribbons with nominal compositions of Co68.5Fe4.0, Si15.0B12.5 (SA), Co68.5Fe3.5Mo3.0Si12.0B12.5 (SMo), Co65.9Fe3.5W3.5Si16.8B11.0 (SW1) and Co64.3Fe2.5W4.7Si16.8B11.0 (SW2) were prepared by rapid quenching technique. As a first step, the pure elements (Fe, W, Co, Mo, B, Si ≥ 99.5%) underwent induction alloying in an argon atmosphere. From the master alloy ingots, amorphous ribbon samples of about 25 μm thickness and 0.7 mm width were produced by melt spinning at tangential velocity of ~30 m/s. The molten metal was ejected by argon gas at an over-pressure of 250 mbar through the orifice in the quartz nozzle positioned at -0.2 mm from the wheel surface.

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![Fig. 1. XRD patterns of Co-based amorphous ribbons of different compositions.](image-url)
field, H. The MI of the sensitive element, inserted in a “microstripe” line, was calculated from the reflection coefficient $S_{11}$ measured by a network analyzer (Agilent E8358A) using an output power of 0 dB (that corresponds to the amplitude of the excitation current across the sample of about 1 mA). The total impedance, its real and imaginary parts were measured as a function of the external magnetic field for a frequency range $0.1 \text{ MHz} < f < 100 \text{ MHz}$. The GMI ratio was defined as follows:

$$\frac{\Delta Z}{Z} = \frac{100}{Z(H_{\text{max}})} \frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})}$$

$$\frac{\Delta R}{R} = \frac{100}{R(H_{\text{max}})} \frac{R(H) - R(H_{\text{max}})}{R(H_{\text{max}})}$$

$$\frac{\Delta X}{X} = \frac{100}{X(H_{\text{max}})} \frac{X(H) - X(H_{\text{max}})}{X(H_{\text{max}})}$$

(2)

where $H_{\text{max}} = 150 \text{ Oe}$ is the maximum applied magnetic field. The maximum values of the total impedance and real part of it ($\Delta Z/Z_{\text{max}}$ and $\Delta R/R_{\text{max}}$) were used for GMI frequency dependences’ analysis. MI sensitivity for total impedance and its real part were denominated as $S(\Delta Z/Z)$ and $S(\Delta R/R)$ accordingly:

$$S(\Delta Z/Z) = \frac{\delta(\Delta Z/Z)}{\delta H}$$

$$S(\Delta R/R) = \frac{\delta(\Delta R/R)}{\delta H}$$

(3)

where $\delta(\Delta Z/Z)$ is the change in the total impedance or real part GMI ratio for $\delta(H) = 0.1 \text{ Oe}$ being the increment for the magnetic field. GMI measurements were made at room temperature. The error in determining the impedance was within 1%. At each frequency, $(\Delta Z/Z)_{\text{max}}$ as the maximum value of the total impedance and $(\Delta R/R)_{\text{max}}$ as the maximum value of the real part of the impedance ratio were determined using $\Delta Z/Z(H)$ and $\Delta R/R(H)$ GMI curves. The direct current resistivity ($R_{DC}$) was also measured for all kinds of ribbons.

The corrosion stability is a very important characteristic from the point of view of applications and it can be evaluated using both complex and simple methods [6,23]. The corrosion of the ribbons was evaluated by the weight loss in solutions of 3.0 M Ortho phosphorous acid (H$_3$PO$_3$) [6] in an ultrasonic bath. The time for the corrosion testing of ribbons was 120 min at room temperature.

### 3. Results and discussions

The XRD patterns (Fig. 1) of the ribbons confirmed the absence of crystalline phases. The M-H curves (Fig. 2) under external load showed the magnetic behavior of the ribbons. The selected properties of amorphous ribbons are summarized in Table 1.

![Fig. 2. M-H curves of Co-based ribbons under external load.](image-url)
of the long range ordering and crystalline phases in all cases under consideration. The ribbons presented a clear amorphous structure and broad diffraction peaks. The results suggested that the incorporation of Mo and W elements has a very small effect on the modification of the amorphous structure. Some of the properties of the ribbons (geometries, DC resistivity and saturation of magnetostriction coefficient), are shown in Table 1. One can see that despite big differences in composition we succeeded to fabricate rapidly quenched ribbons with very similar geometry.

Fig. 2 shows hysteresis loops of the ribbons measured under a different applied load from zero to 950 g. The ribbons showed different behavior under the load due to the difference of their saturation magnetostriction related to the compositional differences. The highest change in M-H curve with respect to the applied load was observed in the case of the SW1 ribbon. The M-H curve of the SW2 ribbon showed no measurable change under different loads and we therefore considered that it had zero a saturation magnetostriction coefficient. Both SW1 and SA ribbons’ M-H curves showed change in the same direction with an increase of the load related to the negative magnetostriction coefficient of about -1.2 for SW1 and -0.6 for SA ribbons. M-H curves for Smo ribbon showed magnetic behavior under load corresponding to close to zero positive magnetostriction coefficient as to be expected for a ribbon of such composition [10].

The coercive force (Hc) and saturation of magnetization (Ms) of the ribbons measured with VSM (not shown here) and the Curie temperature (Tc) of ribbons are collected in Table 1.

The magnetic behavior during the temperature increase was measured at the constant magnetic field H = 100 Oe (Fig. 3, Table 1). Increase of the temperature leads to a decrease of the magnetization of the ribbons. The observed slopes of the M(T) curves in the vicinity of the magnetic transition (Curie temperature) and the values of Tc are different. It can be clearly observed that the addition of Mo reduced the magnetic moment of the as-quenched ribbons: the total content of magnetic elements was the same for SA and Smo samples but both Tc and Ms were lower in the Smo case. In part, this can be explained by the partial substitution of Fe by Co in the Smo ribbon. For SW1 and SW2 samples, the Tc and Ms reductions were not too surprising because the total sum of magnetic elements was also slightly reduced in the ribbons.

Fig. 4 shows the hysteresis loops of the ribbons measured by the conventional inductive method. All of the ribbons were very soft ferromagnets with coercive fields below 0.5 Oe. The saturation magnetizations for all samples are collected in Table 1. The changes in the magnetic moment of the alloy due to the substitution of various elements could be attributed to different effects. For example, differences in the electronic configuration of the replaced elements, variations of the bond state configurations and changes of interatomic distances due to the differences between atomic
radii of the replaced elements could be some of these reasons [24].

Again, the transition from ferromagnetic into paramagnetic state happened in SMo and SW1 and SW2 cases at lower temperature than in the case of the SA ribbon.

A change in composition can also affect the resistance of the ribbon. Table 1 shows that SA and SMo ribbons have rather similar RDC values the same as SW1 and SW2 resistances are similar but W-containing samples show significantly higher resistivity values comparing with W-free samples. The increase of the resistivity for W-containing samples is not too surprising due to high resistivity value of pure W.

Fig. 5 shows frequency dependence of the ($\Delta Z/Z$) max and ($\Delta R/R$) max for Co$_{0.8}$Fe$_{4.0}$Si$_{15.0}$B$_{12.5}$ (SA), Co$_{0.8}$Fe$_{3.9}$Mo$_{3.0}$Si$_{12.0}$B$_{12.5}$ (SMo), Co$_{0.5}$Fe$_{4.3}$W$_{3.0}$Si$_{14.5}$B$_{11.0}$ (SW1) and Co$_{0.4}$Fe$_{4.3}$W$_{4.7}$Si$_{16.5}$B$_{11.0}$ (SW2) ribbons. For ($\Delta Z/Z$) max in the frequency range of 0.1 MHz to 15 MHz the MI maximum increases with the increase of frequency and for higher frequencies gradually decreases for all samples under consideration. The shape ($\Delta Z/Z$) max vs. f curves, displays a maximum at a certain frequency that can be attributed to the competition between the enhancement of skin effect and the reduction of the permeability with frequency growth [25]. For low frequencies below 1.0 MHz all of the curves are very close to each other not showing any significant difference. For f > 1.5 MHz, ($\Delta Z/Z$) max for SW1 ribbon is obviously lower than ($\Delta Z/Z$) max of the other ribbons. The highest $\Delta Z/Z$ value of about 320% at f = 15 MHz was observed for SMo ribbon. For higher frequency range of 35 MHz < f < 87 MHz, ($\Delta Z/Z$) max of the SW2 ribbon is higher than ($\Delta Z/Z$) max of the other ribbons.

The general behavior of the real part of the impedance is different. The increase of the frequency results in the ($\Delta R/R$) max increase until reaching a saturation state for all the ribbons. At low frequencies below 1.0 MHz all of the curves are very close to each other showing no significant difference. For f > 1.5 MHz, ($\Delta R/R$) max of SW1 ribbon is lower comparing with ($\Delta R/R$) max of other ribbons. The SA, SMo and SW2 ribbons ($\Delta R/R$) max curves are similar to each other but ($\Delta R/R$) max values are slightly higher for SMo ribbon.

Frequency dependences of ($\Delta R/R$) max for all of the ribbons were saturated after reaching f = 50 MHz and no significant changes of

Fig. 6. Field dependences of resistance (R), reactance (X), and impedance (Z) of SA (a, b, c) and SMo (d, e, f) ribbons.
\((\Delta R/R)_{\text{max}}\) were observed. The increase of \((\Delta R/R)_{\text{max}}\) can be attributed to an increased scattering due to the greater number of domain walls along the current path in the transverse domain structure [26]. The penetration depth at the different frequencies can be calculated in accordance with Eq. (1). For example, for SA ribbon, with the magnetic permeability of 500 for frequencies of 1 MHz, 15 MHz and 50 MHz the skin depths were 28, 7 and 4 \(\mu\)m, respectively. This means that for high frequencies \(f = 15\) MHz and 50 MHz, the skin depth is smaller than half the thickness of the ribbon and the skin effect is expected to play a relevant role. In contrast for the low frequencies, the skin depth is bigger than half the thickness of the ribbons and therefore the skin effect is less important and the mobility of domain walls may still play a certain role [27]. Other ribbons also showed a similar behavior with an increase of frequency such as the SA one. Therefore precise analysis of impedance, resistance, reactance and MI were conducted for selected frequencies 1 MHz, 15 MHz and 50 MHz.

Figs. 6 and 7 show the field dependence of resistance \((R)\), reactance \((X)\), and impedance \((Z)\) of the SA and SMo, SW1 and SW2 ribbons for selected frequencies (1, 15, and 50 MHz). Both the real and the imaginary components of the impedance show strong dependence on the frequency of the current passing through the ribbons and the applied magnetic field value. It can be observed that \(R, X,\) and \(Z\) increase with increasing frequency and display close to single peak shape their field dependences. Although the general shape is “one peak” type response in good agreement with the shape of the hysteresis loops reflecting the longitudinal effective type of the anisotropy, one can see a complex shape of a double peak in a very low fields interval. Such a behavior was previously observed in as-quenched ribbons and attributed to the strong contribution of the stress-induced surface anisotropy [6,26,28]. The position of the peaks’ maxima roughly correspond to the anisotropy field values.

Fig. 8 shows the magnetic field dependence of \(\Delta Z/Z\) and \(\Delta R/R\) ratios for the SA, SMo, SW1 and SW2 ribbons at \(f = 1\) MHz, 15 MHz and 50 MHz, respectively. The ribbons display \(\Delta Z/Z\) and \(\Delta R/R\) ratios field dependences, which are typical for samples with mixed anisotropies: a small double peak at very low external magnetic field,
Fig. 8. Low field dependences of the $\Delta Z/Z$ and $\Delta R/R$ ratios of Co-based amorphous ribbons of different compositions for selected frequencies (a) $f = 1$ MHz, (b) $f = 15$ MHz and (c) $f = 50$ MHz.

Table 2
Maximum sensitivities for total impedance and its real part GMI ratio calculated for frequencies $f = 1$, 15 and 50 MHz for Co-based amorphous ribbons of different compositions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$S(\Delta Z/Z)_{\text{max}}$ (%/Oe)</th>
<th>$S(\Delta R/R)_{\text{max}}$ (%/Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f = 1$ MHz</td>
<td>$f = 15$ MHz</td>
</tr>
<tr>
<td>SA</td>
<td>14</td>
<td>44</td>
</tr>
<tr>
<td>Smo</td>
<td>102</td>
<td>180</td>
</tr>
<tr>
<td>SW1</td>
<td>51</td>
<td>216</td>
</tr>
<tr>
<td>SW2</td>
<td>54</td>
<td>234</td>
</tr>
</tbody>
</table>
characteristic of samples with transverse anisotropy, which can be probably ascribed to the surface anisotropy contribution. For frequency of 1 MHz (Fig. 8a), SW2 ribbon shows the highest $\Delta Z/Z$ value (about 100%) and the highest $\Delta R/R$ (about 85%). SMo ribbon shows maximum $\Delta Z/Z$ value (about 32%) and maximum value of $\Delta R/R$ (about 320%) at frequency $f$ = 15 MHz (Fig. 8b). At frequency $f$ = 50 MHz (Fig. 8c), maximum value of $\Delta Z/Z$ (about 220%) and maximum value of $\Delta R/R$ (about 440%) were related to SW2 and SMo ribbons, respectively.

The maximum sensitivities with respect to the applied magnetic field were calculated for all ribbons for selected frequencies of 1 MHz, 15 MHz and 50 MHz (Table 2). For all of the frequencies from $f$ = 0.1 MHz to $f$ = 100 MHz the maximum $S(\Delta Z/Z)$ and $S(\Delta R/R)$ sensitivities corresponding to the SA ribbon were much lower than the sensitivities observed for SMo, SW1 and SW2 ribbons. Maximum value of $S(\Delta Z/Z)$ of SA ribbon corresponded to 46%/Oe at $f$ = 20 MHz. The study of the maximum value of absolute sensitivity with respect to the applied magnetic field for SMo, SW1 and SW2 ribbons for the interval of the frequencies from $f$ = 0.1 MHz to $f$ = 100 MHz showed differences between the ribbons. For frequencies from $f$ = 0.1 MHz to $f$ = 6 MHz, SMo ribbon has the highest $S(\Delta Z/Z)$ and $S(\Delta R/R)$ sensitivities. SW2 ribbon has the highest value for the sensitivity in the frequency range of 6 MHz–55 MHz for $S(\Delta Z/Z)$ and of 15 MHz–60 MHz for $S(\Delta R/R)$. For higher frequencies above 55 MHz, both $S(\Delta Z/Z)$ and $S(\Delta R/R)$ for SMo case are higher comparing with sensitivities for the other ribbons. Maximum value of $S(\Delta Z/Z)$ sensitivity of about 240%/Oe was observed at 20 MHz frequency in the case of SW2 ribbon. Therefore, for sensor applications, SMo ribbon is most suitable for the frequencies below 6 MHz or higher than 55 MHz and SW2 ribbon is eligible for frequency interval of 6 MHz–55 MHz. Although an imaginary part is very seldom used for practical purposes Fig. 9 shows $\Delta X/X(H)$ ratios in the interval of very low external fields for selected frequencies. One can see that general shape of $\Delta X/X(H)$ responses is similar to $\Delta Z/Z(H)$ or $\Delta R/R(H)$ curves.

It is known that ribbon surface roughness can play a certain role in determining high GMI behavior in ribbons [29,30]. Fig. 10 shows selected examples of the typical surface roughness of the amorphous ribbons of all compositions (free ribbon surface). One can notice that the general features of surface morphology are very similar for the materials under consideration. The same happens with the wheel surface (photos are not shown here). Therefore, although the surface roughness can contribute to GMI response value these contributions most probably will be comparable to each other.

It is also known, that even a small amount of chemical doping can alter the surface anisotropy, surface domains and hence the MI response of the amorphous ribbons [15,31]. At the same time, establishing such a correlation is a difficult task and the result depends critically on the composition. Complications come from the fact that the surface domains observed in a remnant state are not necessarily reflecting the main domain patterns’ features [32] and a complete magnetization process study is necessary for justified conclusions. This is an interesting goal for further research.

Fig. 11 shows the mass loss of ribbons in the solutions of 3.0 M Ortho phosphorous acid (H$_3$PO$_3$) as a corrosion medium in ultrasonic bath. All ribbons showed linear behavior but with a different slope in the same corrosion medium. The presence of Mo and W elements caused different effect on the corrosion of the as-quenched (SA) ribbon. The average mass loss of the SMo ribbon was significantly lower than the one for other ribbons.

The use of the magnetic field as a transducer for simultaneous detection of many molecular recognition events was reported by Baselt et al., in 1998 [33]. Albeit not always, in the majority of magnetic biosensors magnetic particles play the role of biomolecular labels [34]. Giant magnetoresistance was proposed for the detection of magnetically labelled biomolecules and different kind of sensitive elements were shown to be capable to insure stable detection of magnetic labels [34,35]. In this case, stability of magnetic response in corrosive biological solutions is a crucial requirement. There are materials, which show a high GMI effect but suffer rapid degradation in contact with biofluids [31]. They were shown to be useful for GMI-based monitoring of the reactions at the surface or label-free biosensor detection. Careful GMI and corrosion stability simultaneous evaluations help to define particular applications for each kind of material. With respect to the ribbons
studied in the present work one can clearly see that the SMo composition is the most appropriate for magnetic label detection, whereas SW1 is more indicated for label-free detection regimes.

For further research one can propose both a comparative study of thermal stability of effective magnetic anisotropy in as-prepared samples and temperature dependence of GMI characteristics which can show additional advantages or disadvantages of W-containing amorphous ribbons. We have shown that Mo or W addition can improve the high frequency GMI response in Co-based ribbons. One can also ask the question of how can the present results for the ribbons be compared to wires and microwires? Due to the technological difficulties of fabricating materials with W, there is at present no possibility of making such a comparison, but it would be interesting goal for future studies.

4. Conclusions

$\text{Co}_{68.5}\text{Fe}_{4.0}\text{Si}_{15.0}\text{B}_{12.5}$, $\text{Co}_{68.6}\text{Fe}_{3.9}\text{Mo}_{3.0}\text{Si}_{12.0}\text{B}_{12.5}$, $\text{Co}_{65.9}\text{Fe}_{3.5}\text{W}_{3.1}\text{Si}_{16.5}\text{B}_{11.0}$ and $\text{Co}_{64.3}\text{Fe}_{3.5}\text{W}_{4.7}\text{Si}_{16.5}\text{B}_{11.0}$ amorphous ribbons with similar geometry were obtained by rapid quenching technique. Magnetic properties and giant magnetoimpedance effect in the interval of the frequencies of 0.1 MHz—100 MHz, were comparatively analyzed. All of the ribbons were soft ferromagnets with low coercivity. Additions of Mo and W elements to basic CoFeSiB composition modified the saturation of magnetization and Curie temperature causing their decrease and variation of the saturation magnitostriiction. Frequency dependence of ($\Delta Z/Z$)$_{\text{max}}$ showed that $\text{Co}_{68.6}\text{Fe}_{3.9}\text{Mo}_{3.0}\text{Si}_{12.0}\text{B}_{12.5}$ ribbon has maximum of $\Delta Z/Z$ ratio of 320% at frequency $f = 15$ MHz but for $f > 35$ MHz the $\text{Co}_{64.3}\text{Fe}_{3.5}\text{W}_{4.7}\text{Si}_{16.5}\text{B}_{11.0}$ ribbon shows the highest $\Delta Z/Z$ response. $\text{Co}_{68.6}\text{Fe}_{3.9}\text{Mo}_{3.0}\text{Si}_{12.0}\text{B}_{12.5}$ ribbon also showed better corrosion stability than other ribbons. At the same time, a different sensitivity in the frequency interval of 0.1 MHz—100 MHz was observed and the maximum sensitivity of 240%/Oe at frequency $f = 20$ MHz for corresponded to $\text{Co}_{64.3}\text{Fe}_{3.5}\text{W}_{4.7}\text{Si}_{16.5}\text{B}_{11.0}$ ribbon.

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