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Magnetoimpedance studies on $(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ amorphous ribbons

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In the present work, magnetic and magnetoimpedance (MI) properties of $(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ (x = 0, 3, 5, and 10) amorphous ribbons in the frequency range of 500 kHz–13 MHz are reported. Our studies show that the thermal stability, magnetic behavior, and MI profiles have been strongly influenced by the Si content in amorphous ribbons. The magnetic isotherms show that all the samples of present study attain magnetic saturation values well below 500 Oe with coercivity values in the range of 0.2–0.09 Oe, which suggest ultrasoft nature of the samples. Interestingly, MI follows the magnetization variations with Si content. A maximum MI and field sensitivity of 46% and 4.3%, respectively, have been achieved for 10% B replacement by Si. The results show that the skin depth is strongly modified by the addition of Si, which in turn affects the impedance. The MI profiles show double peak and triple peak nature, which indicates the presence of transverse magnetic domain in all samples.
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INTRODUCTION

Magnetoimpedance (MI) effect is perceived as one of the most attracting research topics owing to their magnetic sensor application properties in modern technology.[1] The MI effect is a classical electromagnetic phenomenon, where the impedance of a ferromagnetic conductor changes significantly under the application of a longitudinal dc magnetic field.[2] The electromagnetic origin of the MI effect is the combination of skin effect and the field dependence of circumferential/transverse magnetic permeability (μ) associated with the circular/transverse motion of magnetic moments (skin depth, $\delta = (2/\sigma\mu f)^{1/2}$ where, σ, μ, and f are electrical conductivity, permeability, and frequency, respectively).[3] Amorphous ribbons are the most promising candidate not only because they exhibit minimum magnetic anisotropy but also the microstructure of amorphous ribbons can be further refined by the addition of nonmagnetic elements like Cu, Si, and Al or by controlled annealing.[4] Apart from the microstructure, composition also plays a significant role in altering the magnetic and MI properties of amorphous or nanocrystalline ribbons. The amount of each element and chemistry among them also play a vital role in determining the best property of the final product.[5] Addition of some selected elements (like Si, Ni, Co etc.) to Fe-rich alloys can also produce nearly zero saturation magnetostriction (λ_s), which helps in obtaining giant magnetoimpedance (GMI) effect. In this work, $(Fe_{70}Co_{30})_{80}B_{20}$ composition has been chosen as crystalline $Fe_{70}Co_{30}$ has a high induction value and suggested as a candidate for high frequency applications. The glass former B assists in reduction of magnetocrystalline anisotropy. Recently, it has been observed that replacement of B with Si results in enhancement of soft magnetic properties.[6] It was also reported that the soft magnetic properties can be altered by gradually increasing the Si content in FeSiCuNbB alloy system. Further, excellent magnetic softness (low coercivity and high permeability) was achieved for Si content of about 11–16 at. %. Therefore, in this work, we have investigated magnetic and magnetoimpedance behavior of $(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ (x = 0, 3, 5, and 10) amorphous ribbons without altering the magnetic constituents of the alloy.

EXPERIMENTAL DETAILS

$(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ (x = 0, 3, 5, and 10) alloy ingots were prepared by arc melting with high purity elemental constituents, and subsequently, amorphous ribbons of 1.6 mm wide, 31 ± 3 μm thick, and a few meters long were prepared by melt spinning technique. The X-ray powder diffraction (XRD) patterns have been recorded to confirm the amorphous phase of all ribbons. The thermal stability and crystallization temperature were determined through differential scanning calorimetric (DSC) measurement in the temperature range of 30 °C–1000 °C with heating and cooling rate of 20 °C/min. Magnetic parameters (saturation magnetization, M_s, and coercivity, H_c) at room temperature were evaluated by using Vibrating sample magnetometer (VSM) (Model: Micro Sence EZ-9) and Coercimeter (Model: CR/02), respectively, applying a varying magnetic field along the length of the ribbon. MI measurements were carried out on 5 cm long ribbons with HP 4192 A impedance analyzer in the frequency range of 500 kHz–13 MHz, allowing a 10 mA alternating current. A magnetic field up to ±100 Oe was applied along the length of the ribbons, using a homemade Helmholtz coil setup. MI and magnetic field sensitivity (η) of MI are defined as $MI(\%) = [(Z(H) - Z(H_{max}))/Z(H_{max})]\%$ and $\eta = (d/dH)[MI(\%)]$, respectively, where Z(H) and $Z(H_{max})$ stand for the impedance in field H and in the maximum field $H_{max} = 100$ Oe, respectively.

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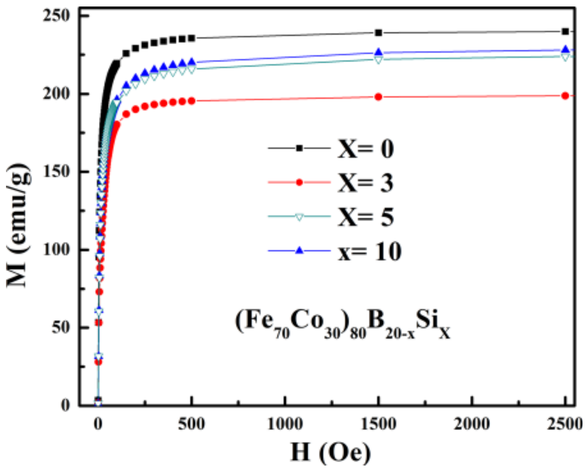

FIG. 1. M-H curves at 300 K for all $(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ ribbons.

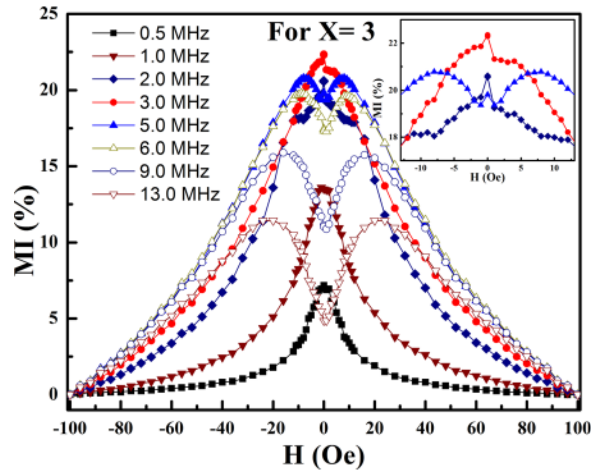

FIG. 3. Variation of MI(%) with magnetic field (H) for $(Fe_{70}Co_{30})_{80}B_{17}Si_3$ (x = 3) ribbons. Inset: SP to DP transition through TP at a low field range.

RESULTS AND DISCUSSION

Amorphous phase of all as-quenched ribbons was confirmed by X-ray diffraction patterns, which was further supported by DSC measurement. The DSC measurement shows a strong exothermic peak at 487 °C (crystallization temperature (T_X)) for $(Fe_{70}Co_{30})_{80}B_{20}$ ribbon, and this peak is shifted towards higher temperature with increasing of Si content. It is interesting to mention that with Si addition, DSC curves show two well separated exothermic peaks, which reveal that Si induces two phase crystallization process. Room temperature magnetization measurements show that all the ribbons (x = 0, 3, 5, and 10) are saturated well below 500 Oe longitudinal magnetic field (Fig. 1). Magnetic saturation value (M_s) of 240 emu/g has been observed for x = 0, and decreased to 200 emu/g for x = 3 ribbon. On further increase of Si content up to x = 10, M_s value increases to 230 emu/g. The coercivity (H_c) measurements by coercimeter suggest that H_c value decreases with increasing Si content. The H_c value significantly changes from 0.2 Oe for x = 0 to 0.09 Oe for x = 10 sample. These magnetic measurements indicate that all the ribbons have soft magnetic properties. It is also interesting to note that soft magnetic behavior is enhanced for the samples with x > 5. Fig. 2 illustrates the MI(%) variation with magnetic field (H) at different frequencies for x = 0 ribbon, which shows that the MI reaches a maximum value ($MI(\%)_{max}$) of 30% at 4 MHz. Inset of Fig. 2 shows the MI curves in low field, which reveals single peak (SP) to double peak (DP) transition at 5 MHz with anisotropy field (H_k) ~ 2 Oe. Fig. 3 depicts that the $MI(\%)_{max}$ decreases to 22% at 3 MHz for x = 3 ribbon, which suggests that addition of Si decreases the MI value, while SP to DP transition occurs at 4 MHz with H_k = 3 Oe. Interestingly, a typical single peak with two plateaus extended beside the sharp central peak has been observed at 2 MHz, which was converted to an uncommon "triple peak" (TP) at a frequency of 5 MHz. Similar features have been reported by Sommer and Chien[8] when CoFeSiB ribbons were annealed under application of transverse magnetic field. Recent researchers show a prominent TP behavior can be observed for the as-quenched amorphous ribbons.[9–11] The MI profiles in Fig. 4 exhibit $MI(\%)_{max}$ of 28% at 6 MHz for x = 5, referring an increase of MI as compared to x = 3 ribbon. For this ribbon, DP behavior has been observed for the whole frequency range (0.5–13 MHz). Fig. 5 describes the MI profile of x = 10 ribbon, and a large $MI(\%)_{max}$ of 46% at 5 MHz has been observed. This variation of MI(%) profile with Si

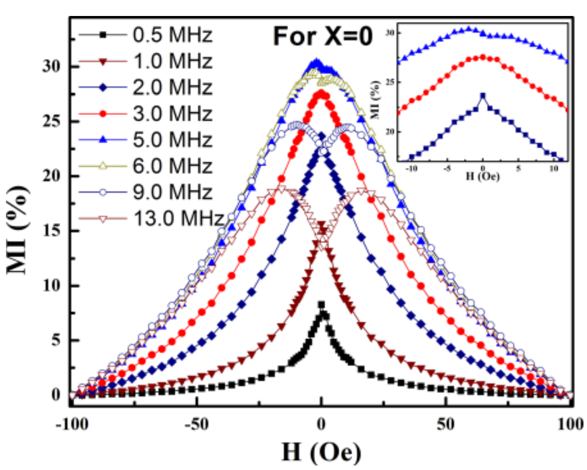

FIG. 2. Variation of MI(%) with magnetic field (H) for $(Fe_{70}Co_{30})_{80}B_{20}$ (x = 0) ribbons. Inset: SP to DP transition at a low field range.

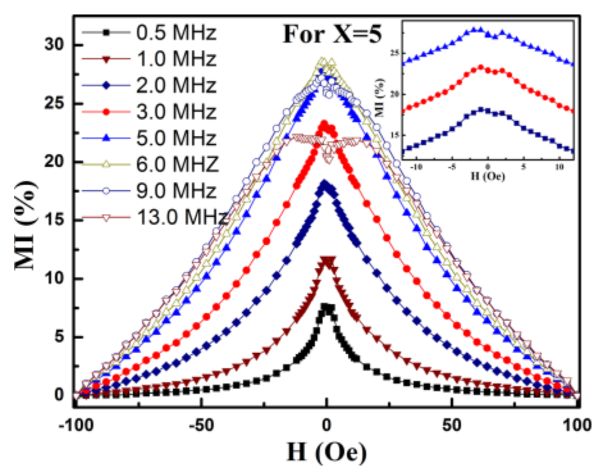

FIG. 4. Variation of MI(%) with magnetic field (H) for $(Fe_{70}Co_{30})_{80}B_{15}Si_5$ (x = 5) ribbons. Inset: SP to DP transition at a low field range.

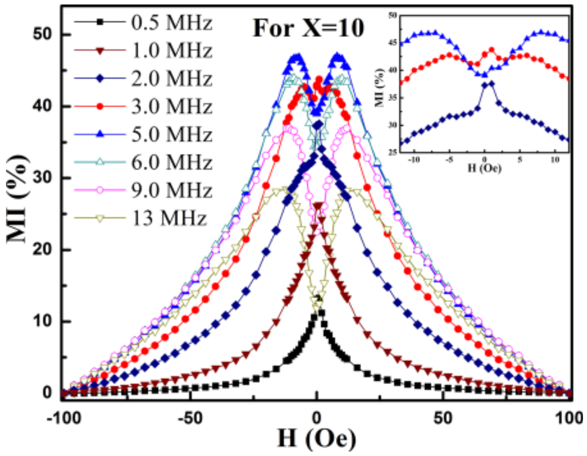

FIG. 5. Variation of MI(%) with magnetic field (H) for $(Fe_{70}Co_{30})_{80}B_{10}Si_{10}$ (x = 10) ribbons. Inset: SP to DP transition through TP at a low field range.

content can be explained by a combination of changes in saturation magnetostriction (λ_s) and magnetic permeability (μ) with Si content in amorphous ribbons. To achieve ultrasoft magnetic properties, the indispensable conditions should be nearly zero λ_s and initial permeability (μ_i) value should be very large. Herzer[7] showed that λ_s and μ_i follow an increasing and decreasing trend when elemental Boron is replaced by Si in nanocrystalline Fe-Cu-Nb-Si-B alloy system. In our Fe-Co-B-Si system, the alteration of MI profile might be due to a combined effect of λ_s and μ_i. The drop in MI(%) value for 3% of Si could be due to enhancement of λ_s, which dominates on μ_i. Further replacement of B by Si ($x \geq 5\%$) produces more α-Fe_3Si phase, which could not be identified by XRD measurement. In this range of Si content ($x \geq 5\%$), μ_i dominates on λ_s, and MI(%) increases gradually for presently studied samples. It is interesting to observe that the $MI(\%)_{max}$ variation with Si-content behaves in the same manner as M_S variation with si. For x = 10 ribbon, a SP to DP transition has also been observed at 5 MHz with $H_k = 7$ Oe. Similar to 3% Si content ribbon, a remarkable central peak with two extended plateaus has been observed at 2 MHz, which transforms to TP at 3 MHz and then converted into DP at 5 MHz. Similar TP behavior was also

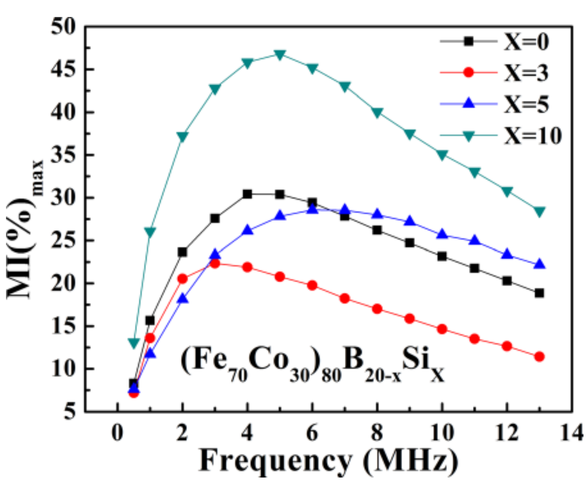

FIG. 6. $MI(\%)_{max}$ variations with frequency for all $(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ ribbons.

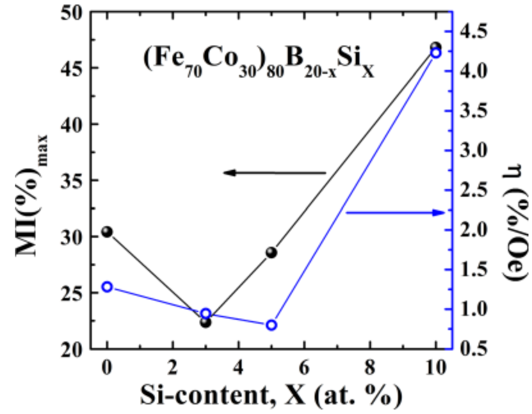

FIG. 7. Variation of $MI(\%)_{max}$ and maximum field sensitivity (η) with Si content for all $(Fe_{70}Co_{30})_{80}B_{20-x}Si_x$ ribbons.

observed for x = 3, but it becomes more evident for x = 10 ribbon, which suggests that Si insists the TP behavior. The mechanism of TP behavior is still quite unclear, though many attempts have been made to understand it.[12] The SP behavior at lower frequency is dominated by domain wall motion (μ_{wall}). On the other hand, the DP appearing at higher frequency is due to damping of domain wall by eddy current, and magnetization process is controlled by domain rotation (μ_{rot}) only. Therefore, the TP behavior might be a typical balance between the domain wall motion and the domain rotation ($\mu_\varphi = \mu_{wall+}\mu_{rot}$) as it is observed at a medium frequency (2–4 MHz). Fig. 6 represents variations of $MI(\%)_{max}$ with frequency. It emphasizes with Si content that $M(\%)_{max}$ shifted to lower frequencies and then towards higher frequency. This is possibly due to the complex behavior of eddy current damping with Si addition. In Fig. 7, $MI(\%)_{max}$ and maximum field sensitivity (η_{max}) have been plotted with Si-content (at. %). This observation reveals that x = 10 sample has a highest $MI(\%)_{max}$ of 46% and a largest field sensitivity of 4.3% among all the investigated samples. From the viewpoint of sensor applications, the present study manifested a systematic way to tailor the magnetic and MI properties with a better field sensitivity by controlling the Si content.

SUMMARY AND CONCLUSIONS

From the present study, it can be concluded that preferable magnetization direction and MI profiles can be altered by the addition of Si to $(Fe_{70}Co_{30})_{80}B_{20}$ alloy composition. A maximum MI(%) and field sensitivity of 46% and 4.3%, respectively, have been achieved for 10% B replacement by Si. A remarkable TP behavior has been observed with Si addition, and it is more evident for x = 10. This might be due to balance of domain wall motion and magnetization rotation at medium frequency.

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