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Giant magnetoimpedance effect in a positive magnetostrictive glass-coated amorphous microwire

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The giant magnetoimpedance (GMI) effect in positive magnetostrictive glass-coated amorphous $Co_{83.2}Mn_{7.6}Si_{5.8}B_{3.3}$ microwire has been studied as a function of a dc magnetic field $-140 < H_{dc} < 140$ Oe and frequency $0.1 < f < 12.85$ MHz. A maximum change of 43% in the MI of the as-quenched sample has been observed around 5 MHz frequency. Heat treatment of the sample by passing a dc current of 50 mA through it enhances the MI value to a large extent (maximum change ~94%) by increasing the outer domain volume and inducing a transverse anisotropy. On the other hand, application of an external tensile stress reduces the GMI value by increasing the inner core domain and developing an axial anisotropy. In an as-quenched sample, the maximum value of MI is observed at $H_{dc} \sim 0$ when measured at frequency $f < 8$ MHz beyond which a two peak MI profile is seen. The heat-treated sample shows this two peak behavior from a much lower frequency (below 1 MHz) and additional peaks at $H_{dc} \sim 0$ for $f > 10$ MHz. Asymmetry in the MI peaks of a microwire has been produced by passing a dc current through the sample during impedance measurement. The magnetization of the as-quenched and heat-treated samples has also been studied to understand the domain structure and magnetoimpedance results.

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INTRODUCTION

The large change in magnetoimpedance (MI), called the giant magnetoimpedance (GMI), in low magnetostrictive amorphous magnetic materials has recently been studied extensively.[1–5] When an ac current, I_{ac} is applied to such materials, their impedance changes sensitively with the change in biasing dc magnetic field. This property can be exploited for various applications such as in recording heads, micromagnetic sensors and so on.[6,7] The field sensitivity of GMI can be as high as 100%/Oe which is much higher than that observed in giant magnetoresistance (usually less than 1%/Oe). The response of GMI to other parameters such as frequency, stress, heat treatment on the samples is also greater than that of magnetization of the sample.

The origin of GMI is different in various frequency regions of the exciting ac current.[8] At low frequencies (~kHz), the field dependence of GMI is attributed to the inductive term of impedance $Z = R + j\omega L$. The time varying ac current produces a circular magnetic field that tends to change the corresponding component of magnetization. As a result, a voltage at the end of the sample is induced. With the application of a dc magnetic field, this induced voltage and hence the inductance of the sample changes. If the frequency of the ac current is increased to MHz region, eddy current is developed and the ac current flows through a thin sheath near the surface of the sample due to skin effect.[9] The skin effect penetration depth δ is given by

$$\delta = \left[\frac{1}{\pi \sigma_c \mu_\varphi f}\right]^{1/2}, \tag{1}$$

where f, μ_φ, and σ_c are, respectively, the frequency, circumferential permeability, and conductivity of the sample. At a particular frequency, the application of a dc magnetic field changes the circumferential permeability μ_φ and hence the penetration depth δ which in turn changes the magnetoimpedance until the value of δ reaches the radius of the sample. In this frequency region where the radius of the sample is much larger than the skin depth δ, both resistance and inductive component of total impedance Z depend on the permeability and contribute to the change in Z with magnetic field.

The Co or Co-Fe based wire shaped samples with low magnetostriction coefficient are the prime candidate for generating GMI. These wire shaped samples consist of a single-domain core having magnetization direction closely parallel to the wire axis and a multidomain external shell with transversely oriented magnetization (radial and circular for positive and negative magnetostrictive samples, respectively).[10] Recently, interest has increased in glass-coated amorphous microwires with 10–25 μm diameter because of their many useful magnetic properties such as their bistable hysteresis loop and large magnetoimpedance.[8,11] These microwires are found to be more promising for several applications compared to wires and ribbons because of their tiny dimensions, superior magnetic properties and protective glass coating. At this time there are few reports on the GMI of negative or zero magnetostrictive microwires.[12,13] Very recently, GMI effect has been reported in a low positive magnetostrictive $Co_{83.2}Mn_{7.6}Si_{5.8}B_{3.3}$ microwire.[8]

Though the change in magnetization and transverse permeability in the outer domains of the samples due to the

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application of a dc magnetic field is considered to be the main reason for GMI,[14] no clear experimental evidence has been reported yet. To verify it, $Co_{83.2}Mn_{7.6}Si_{5.8}B_{3.3}$ microwire has been heat treated by passing a dc current of 50 mA through it. This heat treatment increases the outer domain volume and hence the GMI value by inducing a transverse anisotropy. On the other hand, application of an external tensile stress reduces the GMI value by developing an axial anisotropy and increasing the inner core domain at the cost of outer domains. The GMI is found to be frequency dependent with local maxima. Single peak MI behavior is observed at lower frequencies, whereas, at higher frequencies, two peaks are seen. Additional peaks are observed in the case of heat-treated samples at $H_{dc}\sim 0$ indicating a small contribution to MI from the inner core domain. Development of asymmetry in MI peaks of a glass-coated microwire is reported here. The magnetization of the as-quenched and heat-treated sample has been measured for better understanding of GMI results.

EXPERIMENTAL

Glass-coated amorphous microwires of nominal compositions $Co_{83.2}Mn_{7.6}Si_{5.8}B_{3.3}$ were prepared by Taylor-Ulitovsky method.[8] An x-ray diffractometer (Siemens, Diffractometer-D5000) was used to check the amorphocity of the samples. The diameter of the metallic part of the sample, measured by an optical microscope, is about 18 μm and the thickness of the insulating glass coating is approximately 6 μm. A 12 cm long sample was used for the experiment. The impedance of the sample was measured by a spectrum/network analyzer (Hewlett Packard, 3589 A, 10 Hz–150 MHz) which was connected to a computer data acquisition system. The frequency of the ac current was varied from 0.1 to 12.85 MHz. A Helmholtz coil system was used to apply a dc magnetic field along the axis of the sample during impedance measurement. The axis of the sample as well as that of the Helmholtz coil was kept perpendicular to the direction of the Earth's magnetic field. Axial tensile stresses up to 616 MPa was applied to the microwire for studying the effect of stress on MI. The sample was heat-treated (hence forth termed annealed) by passing a 50 mA dc current for different time durations $t_{an}=5$, 10, 15, and 25 min. The percentage change of MI with applied magnetic field is

$$\frac{\Delta Z}{Z}(\%)=100\times\left[\frac{Z(H)-Z(H_{max})}{Z(H_{max})}\right], \tag{2}$$

where $H_{max}=140\,\mathrm{Oe}$, the maximum applied magnetic field. The asymmetry between the two peaks of GMI profile has been developed by passing a dc current through the sample. The hysteresis loops of as-quenched and annealed microwires were measured by induction method using a flux meter (Walker Scientific, MF3A).

RESULTS AND DISCUSSIONS

The field dependence of MI is shown in Figs. 1 and 2 at 3.5 and 12.85 MHz frequency, respectively, with 1 mA ac current. At frequency $f=3.5\,\mathrm{MHz}$ (Fig. 1), the as-quenched sample shows single peak MI profile with the peak value $[\Delta Z/Z(\%)]_{max}$ at $H_{dc}\sim 0$. The value of $[\Delta Z/Z(\%)]_{max}$ decreases from 29% in the absence of any stress to 15% when a tensile stress $\sigma_{app}=616\,\mathrm{MPa}$ is applied. The MI value increases drastically on annealing the sample by passing a dc current $I_{an}=50\,\mathrm{mA}$. Maximum increase in MI value is observed when it is annealed for $t_{an}=15\,\mathrm{min}$ and the corresponding two peak MI profile at $f=3.5\,\mathrm{MHz}$ with $[\Delta Z/Z(\%)]_{max}\sim 94\%$ is also shown in Fig. 1. If an axial tensile stress is applied to this annealed sample, the value of MI decreases to a large extent ($[\Delta Z/Z(\%)]_{max}\sim 25\%$ for $\sigma_{app}=616\,\mathrm{MPa}$) and the two peak behavior is reduced to one peak behavior.

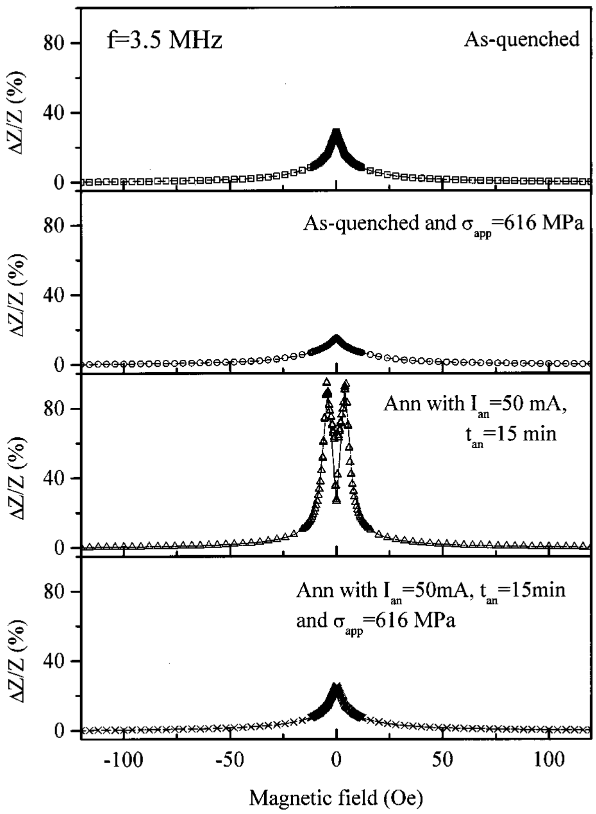

FIG. 1. The variation of percentage change of magnetoimpedance $\Delta Z/Z(\%)$ with dc magnetic field H_{dc} of the as-quenched and annealed ($t_{an}=15$ min) sample in the absence and in the presence of 616 MPa axial tensile stress and for 1 mA ac current with 3.5 MHz frequency.

At 12.85 MHz frequency (Fig. 2), the as-quenched sample shows two peak behavior with much reduced MI value ($[\Delta Z/Z(\%)]_{max}\sim 8\%$). When an axial tensile stress, $\sigma_{app}=616\,\mathrm{MPa}$ is applied to the as-quenched sample, its peak value does not change much but the dip observed at $H_{dc}=0$ decreases substantially. On annealing the sample with $I_{an}=50\,\mathrm{mA}$ for different time durations, the peak value remains almost the same beyond 8 MHz. At 12.85 MHz (Fig. 2) MI results for $t_{an}=15\,\mathrm{min}$ shows a large dip at low field with additional small peaks at $H_{dc}\sim 0$. When a stress, $\sigma_{app}=616\,\mathrm{MPa}$ is applied to the annealed sample, its dip decreases as observed in case of the as-quenched sample under

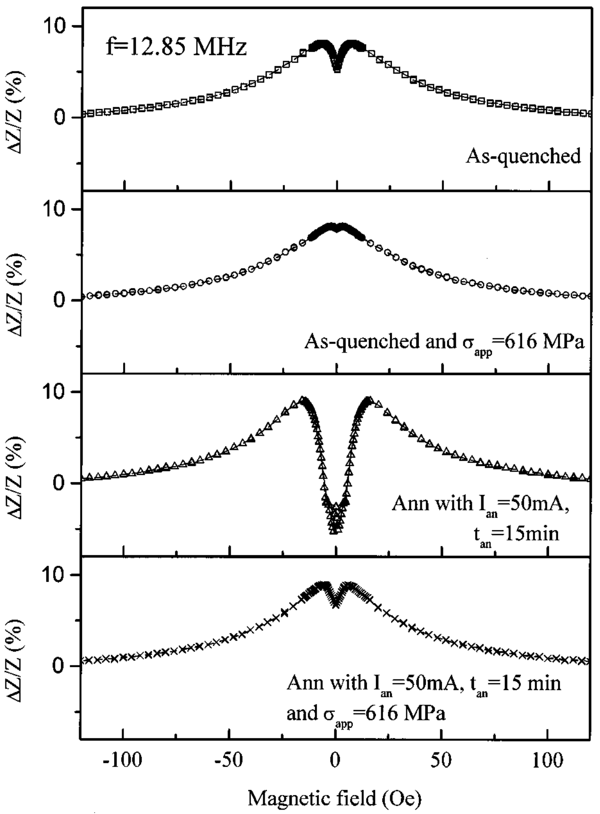

FIG. 2. The variation of percentage change of magnetoimpedance $\Delta Z/Z(\%)$ with dc magnetic field H_{dc} of the as-quenched and annealed ($t_{an}=15$ min) sample in the absence and in the presence of 616 MPa axial tensile stress and for 1 mA ac current with 12.85 MHz frequency.

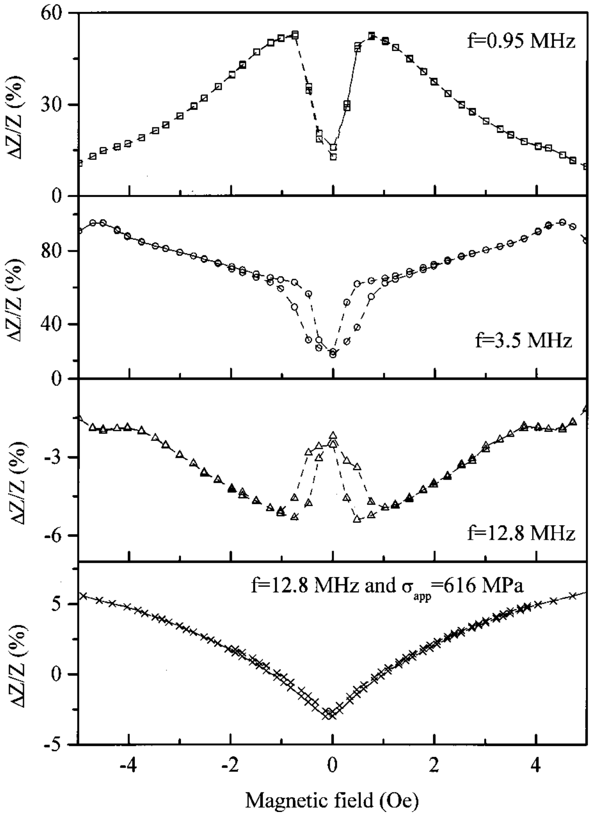

FIG. 3. The variation of percentage change of magnetoimpedance $\Delta Z/Z(\%)$ with dc magnetic field H_{dc} of the annealed sample ($t_{an}=15$ min) in the absence and in the presence of 616 MPa axial tensile stress and for 1 mA ac current with 0.95, 3.5, and 12.85 MHz frequency.

stress and the small peaks observed at $H_{dc}\sim 0$ disappears.

Figure 3 shows the low field MI profile of the sample annealed with $I_{an}=50$ mA for $t_{an}=15$ min. At 0.95 MHz, the peak values of MI appears at a magnetic field $\Delta H_p=\pm 0.8$ Oe with almost no hysteresis loss. On increasing the frequency, the position of the peak shifts towards the higher value of the dc magnetic field and at 3.5 MHz, $\Delta H_p=4.6$ Oe with some hysteresis loss. At 12.85 MHz, additional small peaks appear close to $H_{dc}=0$ with two major peaks at 16.1 Oe (not in this figure). When a stress $\sigma_{app}=616$ MPa is applied to this annealed sample at 12.85 MHz frequency, the small peaks disappear along with the reduction in the dip at $H_{dc}=0$.

Figure 4 shows the frequency dependence of the MI peak value $[\Delta Z/Z(\%)]_{max}$ of the as-quenched as well as the annealed sample in the absence and in the presence of 616 MPa stress applied during measurement. At frequencies below 1 MHz, the MI value of the as-quenched sample is small. From the value of average transverse permeability $\sim 10^3$, the skin depth estimated from Eq. (1) is comparable with the radius of the microwire when the frequency of the current is 1 MHz. This qualitatively explains the observed GMI due to skin depth above 1 MHz as shown in Fig. 4 for the as-quenched sample. The field response of GMI of the as-quenched sample is maximum ($\sim$43%) around 5 MHz. The frequency dependence of $[\Delta Z/Z(\%)]_{max}$ decreases with the increase in stress and reduces to 26% in the presence of 616 MPa stress around 5 MHz. The field response of GMI is improved when the sample is annealed with a dc current $I_{an}=50$ mA. The experimental results are shown in Fig. 4 for annealing time $t_{an}=5$, 15, 25 min. On annealing, MI value changes to a large extent even below 1 MHz and the experi-

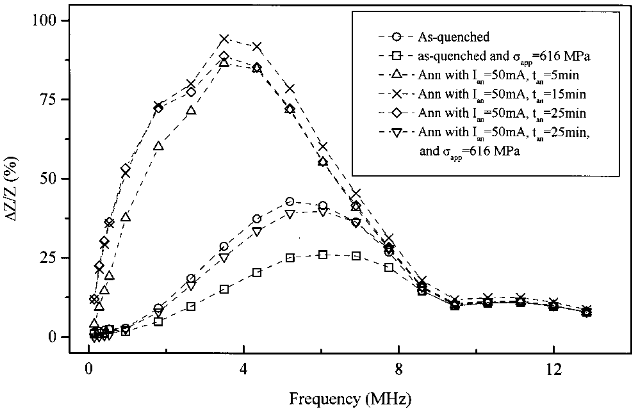

FIG. 4. The variation of maximum percentage change in magnetoimpedance (i.e., the peak value of GMI), $[\Delta Z/Z(\%)]_{max}$ with frequency of the as-quenched and annealed samples in the absence and in the presence of 616 MPa axial tensile stress and with 1 mA ac current.

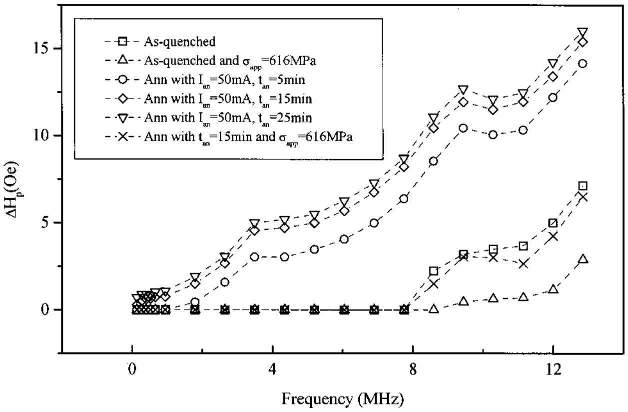

FIG. 5. The frequency dependence of the peak positions of GMI, ΔH_p, of the as-quenched and annealed samples in the absence and in the presence of 616 MPa axial tensile stress with 1 mA ac curent.

mental results corresponds to $t_{\mathrm{an}}=15\,\mathrm{min}$ show the best response with $[\Delta Z/Z(\%)]_{\max}\sim 94\%$ at 3.5 MHz. The maximum field sensitivity of GMI, $1/\Delta H(\Delta Z/Z)$, of the as-quenched sample is ~7%/Oe at 5.0 MHz where $(2\Delta H)$ is the full width of the magnetic field at half maximum of $\Delta Z/Z(\%)$. The maximum field sensitivity is increased to ~14.5%/Oe at 3.5 MHz when the sample is annealed for 15 min. The MI value decreases when a tensile stress is applied to the annealed sample and the results are also shown in Fig. 4 for $\sigma_{\mathrm{app}}=616\,\mathrm{MPa}$ on the sample annealed for 15 min.

The frequency dependence of the peak position ΔH_p of the as-quenched and annealed sample is shown in Fig. 5. For the as-quenched sample, the double peak behavior appears after 8 MHz while on annealing the sample, this two peak profile begins at a much lower frequency. In all cases, the position of peak, ΔH_p shifts toward higher values of magnetic field with the increasing frequency. Application of an external stress reduces the ΔH_p value, even two peak structure is reduced to one peak structure at low frequencies. For example, when the sample is annealed for 15 min, double peaks appear from the lowest frequency (0.14 MHz) used for the experiment while in the presence of 616 MPa stress, this annealed sample shows single peak behavior up to 8 MHz frequency.

Asymmetry between the two peaks of the stress annealed sample ($t_{\mathrm{an}}=25\,\mathrm{min}$) has been developed by passing a dc current through the sample during MI measurement along with the ac current I_{ac}. Figure 6 shows the asymmetry MI (AMI) for $I_{\mathrm{ac}}=1\,\mathrm{mA}$ and $I_{\mathrm{dc}}=\pm 1\,\mathrm{mA}$ at frequency $f=0.8\,\mathrm{MHz}$. On changing the direction of I_{dc}, asymmetrical behavior is also reversed. Figure 7 shows the frequency dependence of the difference between the two peak height, $\Delta Z_{pp}(\%)$. The difference between the two peak heights is maximum around 1 MHz frequency.

The dc axial hysteresis loops of the as-quenched sample in the absence of any stress and in the presence of stress $\sigma_{\mathrm{app}}=452\,\mathrm{MPa}$ are shown in Fig. 8. A sudden large change in magnetization at very low field and a slow increase in magnetization at higher field is observed. The application of an external stress increases the initial low field jump and the magnetic softness of the sample. The coercivity H_c of the as-quenched sample changes from ~70 mOe at $\sigma=0$ to ~50 mOe at $\sigma=452\,\mathrm{MPa}$. The hysteresis loop of the same sample annealed for 25 min with $I_{\mathrm{an}}=50\,\mathrm{mA}$ has also been plotted in the same figure. On annealing the sample, the initial jump in magnetization is reduced.

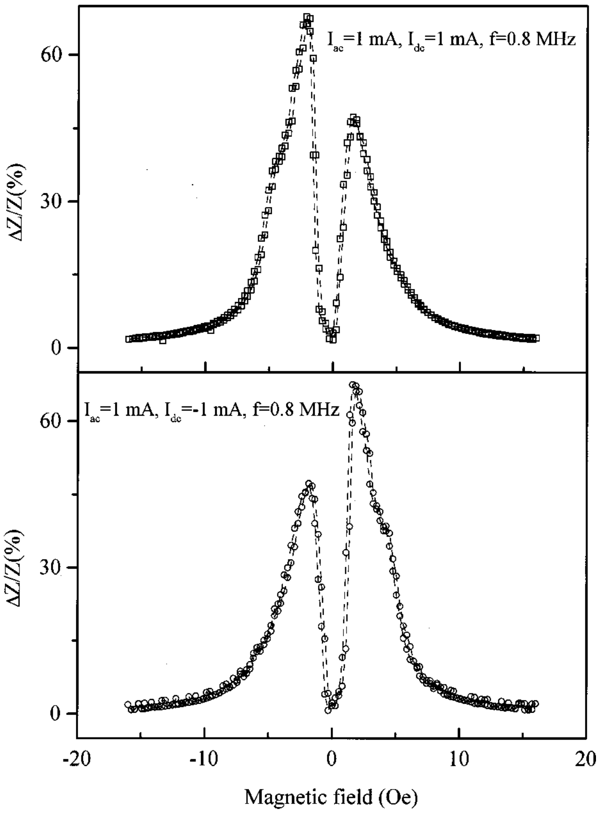

FIG. 6. Asymmetric magnetoimpedance shown by the sample annealed for $t_{\mathrm{an}}=25\,\mathrm{min}$. The measurement was performed with $I_{\mathrm{ac}}=1\,\mathrm{mA}$ at 0.8 MHz and $I_{\mathrm{dc}}=\pm 1\,\mathrm{mA}$.

As mentioned before, the large change in MI in very low magnetostrictive amorphous magnetic materials is because of the change in penetration depth, δ due to the change in

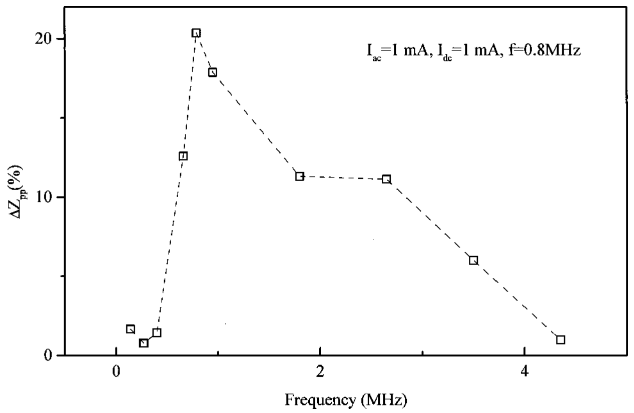

FIG. 7. The frequency dependence of the difference between the two peak height in case of asymmetric MI, $\Delta Z_{pp}(\%)$. AMI was obtained with $I_{\mathrm{ac}}=1\,\mathrm{mA}$ at 0.8 MHz and $I_{\mathrm{dc}}=1\,\mathrm{mA}$.

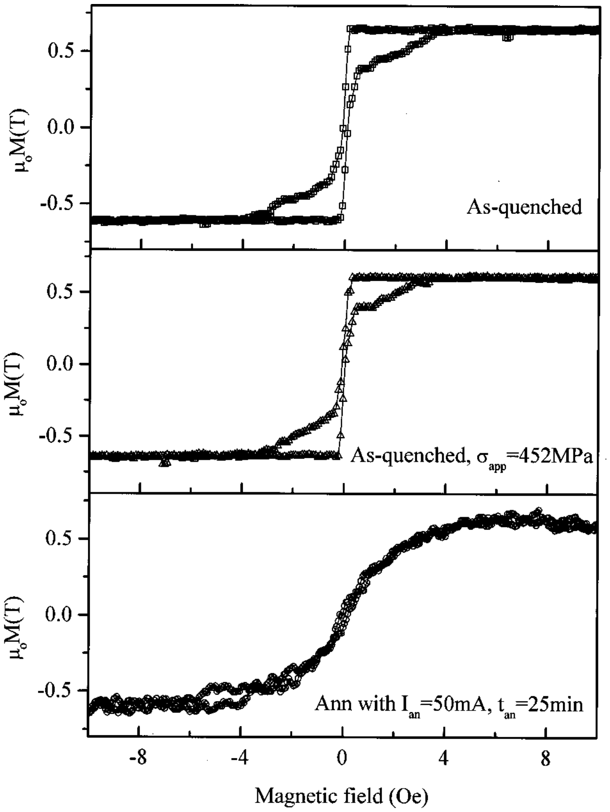

FIG. 8. The hysteresis loops of the as-quenched sample in the absence and in the presence of 452 MPa axial tensile stress and of the sample annealed with $I_{\mathrm{an}}=50\,\mathrm{mA}$ and $t_{\mathrm{an}}=25\,\mathrm{min}$.

transverse permeability μ_φ according to Eq. (1) by an external dc magnetic field H_{dc}. The hysteresis loop and domain structure of the microwire suggests two permeability peaks against magnetic field, one at the switching field of the inner core domain and the other near the anisotropy field of the outer shell. These two maxima in transverse permeability should give rise to two MI peaks on both sides of $H_{\mathrm{dc}}=0$. At lower frequencies, the anisotropy field is close to the switching field and the two peaks from the two domain regions cannot be distinguished. As a result of it, single peak MI behavior is observed (Fig. 1) with the peak value at $H_{\mathrm{dc}}\sim 0$ as the switching field of the microwire is very small ($\sim$70 mOe). With the increase in frequency of the ac current, the anisotropy field of the outer shell shifts more towards the higher field compared to the switching field as the domain wall displacement in outer shell is more affected by increase in frequency than the moment rotation in the inner domain. This explains the higher values of ΔH_p at higher frequencies (Fig. 2). At 12.85 MHz (Fig. 2), the GMI peaks near $H_{\mathrm{dc}}=0$ due to inner core domains are not visible in case of as-quenched sample as the domains in the outer shell contributes to GMI more than the inner domains whereas the same peaks are observed for annealed sample as the contribution from the outer domains is much less around $H_{\mathrm{dc}}=0$ in the annealed sample.

As the annealing current generates a circular magnetic field during heating, a transverse anisotropy is developed within the sample resulting an increase in outer domain volume with magnetization direction perpendicular to the wire axis. As a result of it, the GMI value increases (Fig. 1). The two peak GMI profile is observed at much lower frequency in the annealed sample (Fig. 2) compared to the as-quenched one (Fig. 1) due to the increase in anisotropy field on annealing when measured along the axis of the wire. The application of an axial tensile stress has an effect opposite to that of current annealing. The stress generates a uniaxial anisotropy along the axis of the wire (as the axial magnetic field) increasing the inner domain volume at the cost of outer domains. This results in the decrease in GMI on applying tensile stress as found in Fig. 1. The magnetoelastic anisotropy developed by the axial tensile stress enhances the magnetic softness along the wire axis and reduces the switching and anisotropy field (Fig. 8). As a result of it, ΔH_p, the position at which the GMI peaks appear, shifts towards the lower value of magnetic field with the increase of stress (Fig. 5) and even the single peak behavior is reproduced at sufficiently high stress. The magnetostriction coefficient λ_s can be estimated[15] using the expression $\lambda_s=(\mu_0 M_{s/3})(dH_k/d\sigma)$ and considering that the GMI peaks appear at the anisotropy field H_k. Taking $\mu_0 M_s=0.7\,\mathrm{T}$, the value of λ_s for the sample annealed for 15 min is $\sim 4\times 10^{-7}$.

At frequencies below 1 MHz ($r<\delta$), the peak value of GMI is not very large as the contribution to GMI arises from the induced magnetoinductive voltage. When the frequency is higher than 1 MHz and $r\gg\delta$, higher values of MI are obtained as a consequence of skin effect. Beyond 8 MHz, domain-wall motion is strongly damped owing to eddy currents resulting in a small MI effect. Asymmetry in MI is developed as a result of the helical anisotropy generated within the sample due to the combined effect of circular dc magnetic field produced by the dc current and the applied axial dc magnetic field.[7,16]

CONCLUSIONS

Glass-coated amorphous microwire with nominal composition $Co_{83.2}Mn_{7.6}Si_{5.8}B_{3.3}$ and low positive magnetostriction coefficient are found to show giant magnetoimpedance effect in the range 1–8 MHz frequency. A maximum change of 43% in MI of the as-quenched sample has been observed at 5 MHz frequency. Heat treatment of the sample by passing a dc current of 50 mA through it enhances the MI value (maximum change $\sim$94%) by increasing the outer domain volume and inducing a transverse anisotropy. On the other hand, application of an external tensile stress reduces the GMI value by increasing the inner core domain and developing an axial anisotropy. In case of as-quenched sample, the maximum value of MI is observed at $H_{\mathrm{dc}}\sim 0$ when measured at frequency $f<8\,\mathrm{MHz}$ beyond which two peak MI profile is seen. The heat-treated sample shows this two peak behavior from a much lower frequency (below 1 MHz) and additional peaks at $H_{\mathrm{dc}}\sim 0$ for $f>10\,\mathrm{MHz}$. Asymmetry in the MI peaks of a microwire has been developed by passing a dc current through the sample during impedance measurement. The magnetization measurement indicates two kinds of domain structure within the sample, a single domain axial core and a multidomain outer shell with transverse magnetization. The outer shell increases on heat treatment with a dc current whereas the inner domain increases when an axial stress is applied. The GMI results can be explained considering the skin effect at high frequency and the change in transverse permeability and hence the penetration depth with the change in the applied dc magnetic field.

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