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Parametric controls on giant magnetoimpedance (GMI) behaviour of CoFeSiBCr amorphous wires for prospective sensor applications

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ABSTRACT

Investigation is focused on the effect of different parametric controls like driving frequency, amplitude of the alternating current (ac), direct current (dc) bias field and anisotropy field (H_k) on the Giant Magneto-Impedance (GMI) properties of rapidly quenched soft magnetic $Co_{66}Fe_2Si_{13}B_{15}Cr_4$ amorphous wires developed by in-water quenching technique. Optimal controls of these parameters like driving frequency and amplitude of the ac were found to display a sensitive change in GMI properties at optimal frequency of 5 MHz and 5 mA driving current. The influence of these controls on the output factors like maximum GMI ratio (GMI_{max}), transition from single peak (SP) to double peak (DP), field sensitivity of GMI (η) and anisotropy field (H_k) throw light on the application of the developed wires for sensors. In addition to high H_k, driving frequency of 5 MHz also delivered a combination of desirable sensor properties like high level of sensitivity and its enhanced span of stability. Joule heating further improved the GMI response of the material through current annealing at a current density of 5 A/mm^2.

1. Introduction

Technological development in magnetic sensors witnessed a paradigm shift with the introduction of rapidly quenched microwires (diameter < 100 μm) bearing Giant Magneto-Impedance (GMI) response [1]. The sensor controlling parameters like frequency [2] and driving alternating current [3–5] play a critical role in this response. These controls are alloy specific and therefore, need to be optimized for enhanced sensitivity of the microwires. The parameters defining GMI characteristics like single peak (SP) and double peak (DP) are dependent on the axial anisotropy and circular anisotropy respectively [6–8]. In most of the materials the rapidly quenched microwires belong to either Fe-, Co-, or equi-atomic CoFe-based alloys. Investigations on GMI behaviour have been carried out on alloys bearing Co:Fe::50:50 stoichiometric selections [9,10]. In this type of alloys, the effect of Cr on the soft magnetic properties and the magnetoimpedance behaviour was studied and found that impedance responses remain unaltered when at % of Cr is greater 4, although the coercivity decreases continuously with the addition of Cr. In recent investigations, focus is on Co-based-low-Fe fractions alloy microwires [11]. Such compositional selections with appropriate stoichiometry is expected to deliver low magnetostrictive coefficients 'λ_S' and better GMI characteristics. A noticeable value of GMI on a Co-rich nearly zero magnetostriction constant amorphous ribbon has been reported [12]. In the present study, Co-based low Fe fraction alloy with Cr_4 (at %) has been investigated in the form of microwire.

It is well-known phenomena that dc field in microwires influence the circular permeability [14]. Thus, the alloys bearing very low negative magnetostriction have circular domain structure which ultimately favours circumferential permeability leading to high GMI output [15]. As the microwires are water quenched, they have a stress across the girth of the wires and consequently, skin depth and associated parametric controls like frequency, bias alternating current and magnetizing field influence the GMI behaviour. In addition to alloy development, heat treatment methodologies like furnace annealing [16] and Joule heating [17,18] also enhances the magneto-impedance response of the microwires. Investigators have reported [16] on the effect of annealing on magnetic properties and GMI effect in $Co_{69}Fe_4Cr_4Si_{12}B_{11}$ amorphous microwires with diameters of 90 μm and 55 μm. Thicker wires (d = 90 μm) showed inferior GMI (approx 120%) than annealed at 400 °C warm drawn wire of diameter 55 μm (GMI_{max} 175%). In addition to annealing behaviour, there are also reports [19] on the effect of temperature and elastic tensile stresses on magneto-impedance response of amorphous foils. The effect of elastic tensile stresses

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on magnetoimpedance represents different characteristics at different temperature ranges. In the present decade, constant efforts are being laid to focus more on application criteria of the GMI technology. The potential applications involve development of sensors or sensing devices for non-destructive evaluation of degradation in materials that occur in components during extended period of service [21,22]. Such applications indeed demand high sensitivity of the GMI sensor materials. In order to meet such requirements, the GMI ratio as well as the field sensitivity of the sensing material has to be improved. Furthermore, a stable range of the field sensitivity needs to be optimized in order to exploit the full potential of the sensing device. Investigators have been demonstrated the GMI effect as well as the field sensitivity can be improved through stress-current anneal treatment in the case of $Co_{68}Fe_{4.5}Si_{15}B_{12.5}$ melt extracted wires [11]. Enhancement of GMI characteristics also pertains to the absence of hysteresis, good linearity, stability against temperature variation and better field sensitivity. Such desired sensitivity coupled with high resolution has been reported for thin film sensing element [13].

Most of the previous researches on Giant Magnetoimpedance (GMI) effect have been documented pertaining to scientific and fundamental aspects of the GMI phenomena with special reference to impedance ratio and peak values. However, from sensor application point of view, the requirements are not limited to these parameters only. The level of sensitivity and stability of the GMI material under external magnetizing field at various determinant frequencies are some critical issues to be addressed for sensor application. The present investigation is an approach towards addressing these issues with special reference to magneto-impedance responses of Co-based FeSiBCr amorphous wires. Emphasis has been laid on the field sensitivity level and its span of stability with varying frequencies.

2. Experimental

Amorphous soft magnetic $Co_{66}Fe_2Si_{13}B_{15}Cr_4$ wires of diameter 100 μm were fabricated by in-water quenching technique in the laboratory. Details of the wire preparation have been described elsewhere [9,20]. About 8 cm in length of the wire was taken for GMI properties measurement using four probe techniques through automated GMI measurement system. In this system, an alternating driving current, I_{ac}, was fed through the wire positioned at the centre of a Helmholtz coil which was used to apply a dc magnetic field along the axis of the sample. The impedance was measured through precision impedance analyzer (Agilent make Model: 4294A). The GMI study was carried out in the frequency range 0.1 MHz to 10 MHz and the amplitude of the driving ac was 5 mA. The GMI ratio was calculated using relation (1):

$$\frac{\Delta Z}{Z}\% = \frac{Z(H) - Z(H_{sat})}{Z(H_{sat})} \times 100\% \tag{1}$$

where H_{sat} is the maximum dc applied field.

The field sensitivity of GMI (η) with respect to applied magnetizing field 'H_{dc}' was derived from GMI responses using the relation (2)

$$\eta = \frac{\partial Z}{\partial H} \tag{2}$$

The measurement of Joule heating effect was carried out by passing ac current through the amorphous wires using lock-in amplifier (Stanford Research System, Model: SR830 DSP) at a frequency 1 kHz to Helmholtz coil and simultaneously observing the ac output response (susceptibility) of the sample.

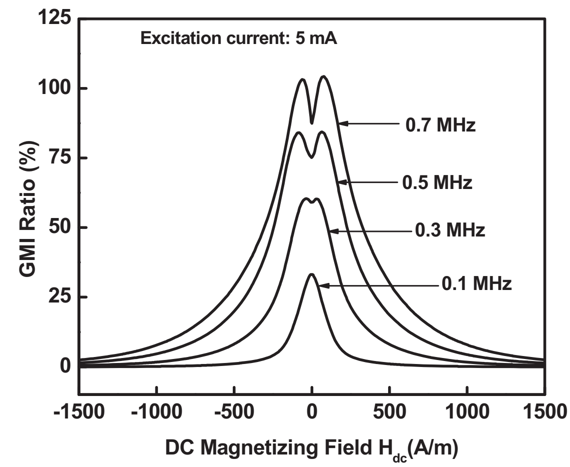

Fig. 1. GMI ratio as a function of dc magnetizing field H_{dc} in the frequency range 0.1–0.7 MHz.

3. Results and discussions

The variation of magneto-impedance with the dc magnetizing field H_{dc} was obtained in the presence of an ac driving current of 5 mA. The GMI ratio of the amorphous wire obtained in the frequency range 0.1–10 MHz are plotted in Figs. 1 and 2 respectively. It was observed from Fig. 1 that single peak (SP) GMI behaviour (i.e. highest GMI value at $H_{dc} = 0$) observed at 0.1 MHz transformed to double peak (DP) (i.e. highest GMI value at $H_{dc} \neq 0$) behaviour at frequencies 'f' of 0.3 MHz. The cause of the transition from SP to DP is correlated to axial and circular anisotropy field. At lower frequency, the axial anisotropy field is dominant. However, at higher frequencies (≤0.3 MHz), the circular anisotropy field plays a pivotal role for the transition from SP to DP [6,18]. Investigations support that the phenomena can be interpreted on the basis of frequency dependence of circumferential permeability (μ_φ) of the wire. Such SP and DP behaviour of GMI are due to the contribution of domain wall movement ($\mu_{\varphi dw}$) as well as magnetization rotation ($\mu_{\varphi rot}$) process towards circumferential permeability (μ_φ) which is mathematically given as $\mu_\varphi = \mu_{\varphi dw} + \mu_{\varphi rot}$ [7,8]. At low frequencies when the penetration depth is high, magnetization along the wire axis is facilitated leading to easy domain wall movement along the wire length. Thus, axial permeability due to $\mu_{\varphi dw}$ increases. However, magnetization rotation which is more

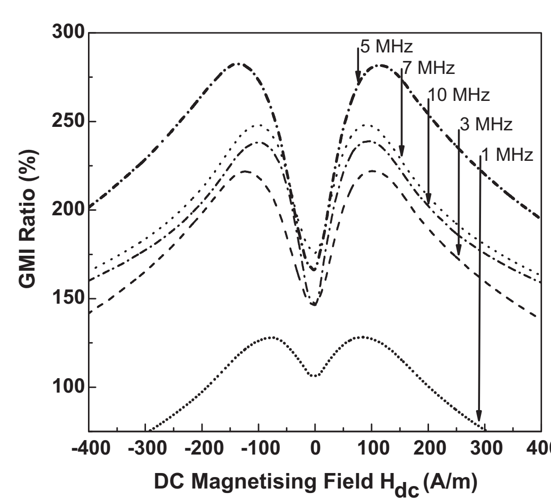

Fig. 2. GMI ratio obtained in the frequency range 1–10 MHz as a function of dc magnetizing field H_{dc}.