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The Influence of Series and Parallel Current Flowing Through Two Paralleled Co-Based Amorphous Wires on Giant Magneto Impedance Effect

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Abstract

Background: Giant Magneto Impedance (GMI) is effectively enhanced by the mutual magnetic interaction between two wires arranged in parallel setup. The direction of current flowing through two wires (series or parallel current mode) has a key role in this change. **Methods:** The aim of this research is to study the GMI properties of series and parallel current flowing through two amorphous Co-based wires in parallel setup and compare it to a single wire. Therefore, the wires with stoichiometric formula $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ were prepared by in-rotating water spinning method with diameter about 125 μm. **Findings:** The best GMI response measured in series current mode and 8 mm distance between two wires. The GMI ratio increases from 300% of single wire to 480% of two wires in series current mode. However when the current flowing through two wires is in parallel mode, the GMI ratio decreases to 180% which is due to reduction of effective magnetic field. For two-wire system in series current mode, the magnetic interaction is stronger than parallel current configuration. **Application:** These results demonstrate that the GMI response could be effectively improved in two-wire series current system, which is useful for the application of low dimension and high sensitive GMI sensors.

Keywords: Amorphous Co-based Wire, Magneto Impedance, Series and Parallel Current Configurations, Sensitivity

1. Introduction

A large change in the complex impedance of a soft ferromagnetic conductor material when an ac current ($I=I_o \sin\omega t$) with high frequency flows through it in the presence of an external dc magnetic field is Giant Magneto Impedance effect (GMI)[1–5]. The GMI effect is directly related to changes in the skin depth (δ_m) that depends on the circumferential permeability (μ_φ), electrical conductivity (σ), frequency (f) and that is expressed by:

$$\delta_m = \frac{1}{(\pi f \sigma \mu_\phi)^{\frac{1}{2}}} \tag{1}$$

Since application of a dc magnetic field increases the skin depth and thereby decreases the impedance. A GMI effect should exist in materials having 1. Low resistivity, 2. High effective permeability, and 3. Low relaxation parameter. The GMI effect has been of increasing interest in sensor technology because of its high sensitivity, quick response, low cost, easy handling, minimal environmental impact, and stability in operation. It has been detected in a wide range of soft ferromagnetic materials, such as wires, ribbons, and thin films[1]. One way to miniaturize sensors was techniques of series and parallel sensor elements. The magnetic properties of the two-wire system is significantly changed than in each single wire[6,7]. So the GMI effect was influenced in a two wires and maybe increase or decrease. According to[7], the GMI response of amorphous Co-based microwires could be effectively modified in the two-wire system with parallel configuration and parallel current flow. Beside[8] reported that the GMI effect decreases in multiple micro wires, while in other research the authors found the GMI response is enhanced and increases with the number of micro wires[9,10]. In[11] authors also reported that the stability of the GMI response is enhanced in the multiple micro wire arrays.

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In all the above-mentioned reports, the effect of the series or parallel current flowing through the two wires on GMI of Co-based amorphous wires was not studied. However, the direction of current in two parallel wires is important, the aim was to compare and obtain the influence of series and parallel current flowing through two amorphous Co-based wires ($Co_{68.15}$ $Fe_{4.35}$ $Si_{12.5}$ B_{15}) which are parallel to each other on giant magneto impedance effect.

2. Experimental

The magnetic properties of as-quenched $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ (diameter ≈ 125 μm) amorphous wire prepared by in-rotating water spinning technique is studied. Two series and parallel current configurations were used in this work as shown in Figure 1. A_1 configuration: Two parallel wires were placed on sample holder and current were chosen in a way the series current flows through the two wires (see Figure 1(a)). A_2 configuration: Two parallel wires were placed on sample holder and current were chosen in a way the parallel current flows through the two wires (see Figure 1(b)). The single wire of 30 mm in length was first placed into a measuring sample holder. When the measurement of GMI effect for single wire was completed, then the other wire was also connected with the former one at different distances d in the same sample holder with a parallel connecting mode. The impedance measurement was investigated at room temperature of about 25 °C.

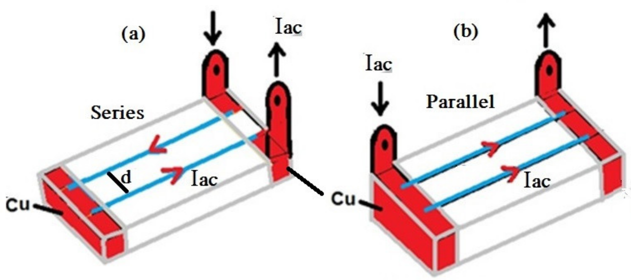

Figure 1. Schematic view of two current configurations. **(a)** Series current (A_1 configuration). **(b)** Parallel current (A_2 configuration).

The GMI system measures the voltage drop across the sample as a function of the external magnetic field. It includes a digital function generator which provides the ac current of I_{pp}= 14 mA (It is worth noting that the measurements were carried out in several different currents which the best results were obtained in 14 mA), and an oscilloscope that determines the variation in the voltage. In GMI measurements, all electrical contacts are prepared with Ag painting and the magnetic field is applied perpendicular to the earth magnetic field. The required dc magnetic field, H, for investigating the magnetic field dependent GMI, is provided by a long solenoid which is perpendicular to the earth's magnetic field. Figure 2 shows a schematic view of the GMI measurement setup.

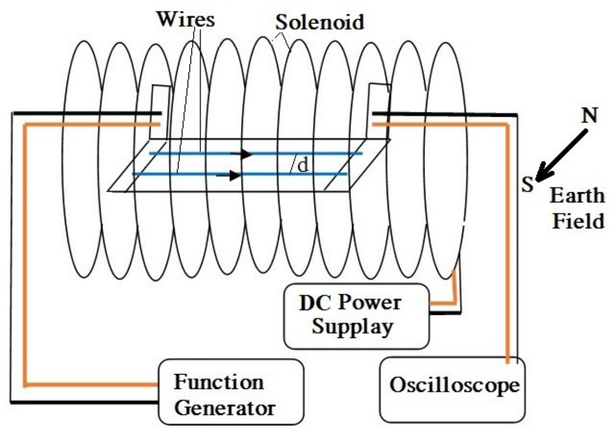

Figure 2. Schematic view of the apparatus for GMI measurement.

The GMI ratio for the total impedance is defined as follows[12]:

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

where Z(H) represents the electrical impedance and H_{max} stands for the maximum applied magnetic field. This maximum value is considered to be 200 Oe. The dc magnetic field sensitivity of GMI is defined as[10]:

$$\xi = \frac{d(\frac{\Delta Z}{Z}\%)}{dH} = \frac{d(GMI\%)}{dH} \tag{3}$$

3. Results and Discussion

To determine the best frequency for GMI measurements in single wire and two wires (A_1 and A_2 configuration), the GMI as a parameter of frequency (2, 4.5 and 6 MHz) was measured. As can be seen in Figure 3, the GMI for 4.5 MHz in all setups has a maximum value as compared with the other frequency. Also to determine the optimum distances between two wires in A_1 and A_2 configurations for GMI measurements, the GMI as a parameter of distance (5, 8 and 12 mm) was measured. As can be seen in Figure 4, the GMI for 8 mm distance is maximum. Therefore, further measurements were performed using this current frequency and distance (4.5 MHz and 8 mm).

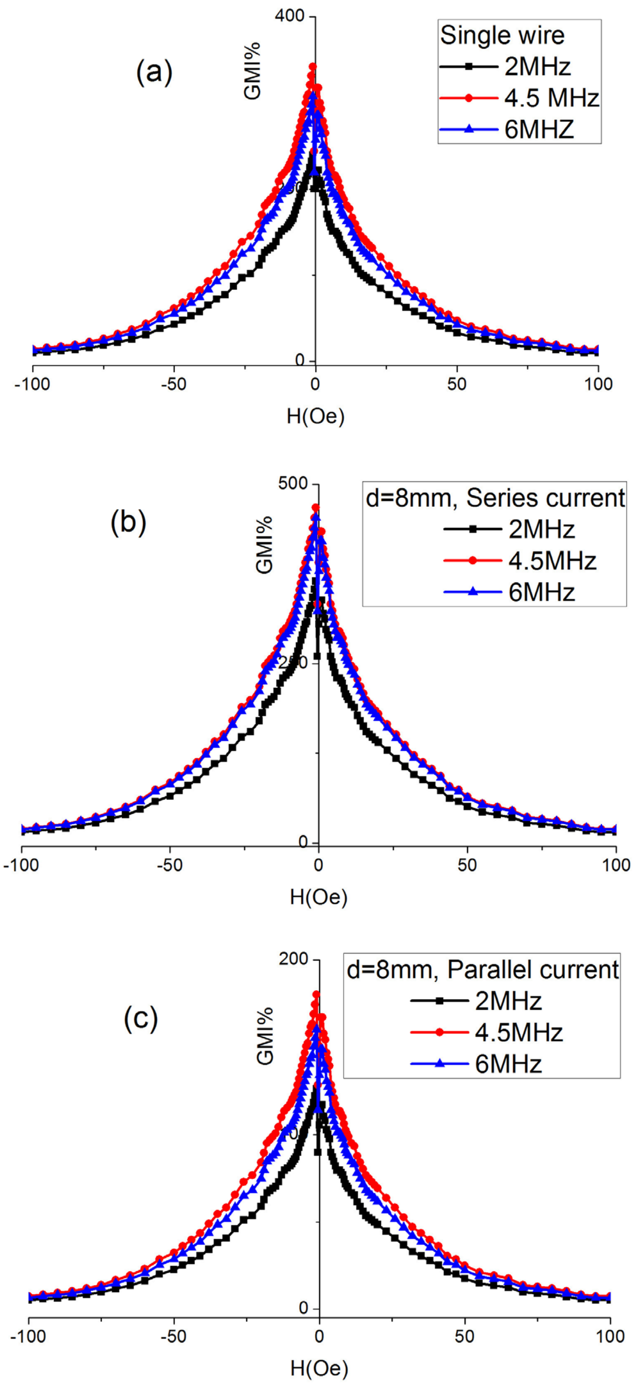

Figure 3. (Color online) GMI profiles of single wire and two wires at different frequencies.

Both the change in magneto impedance and the variation in μ_φ must be considered with each other. It has already been accepted that for a material with longitudinal anisotropy, the magnetization rotation is often dominant over domain wall motion. Consequently the μ_φ and the $\Delta Z/Z$ indicate a monotonic decrease as we increase the magnetic field with a peak at $H_{dc}= 0$. Because of the domination of the magnetization rotation to contribute the μ_φ at high frequencies, where domain wall motion is greatly suppressed, the peak is broader and taller. Higher frequencies also correspond to a stronger skin effect so it increases the overall impedance. It is clear that applying H_{dc} lead to a sharp decrease in μ_φ. Such an interpretation has also been mentioned for the amorphous micro wire with nominal composition of $Co_{68}B_{15}Si_{10}Mn_7$[6].

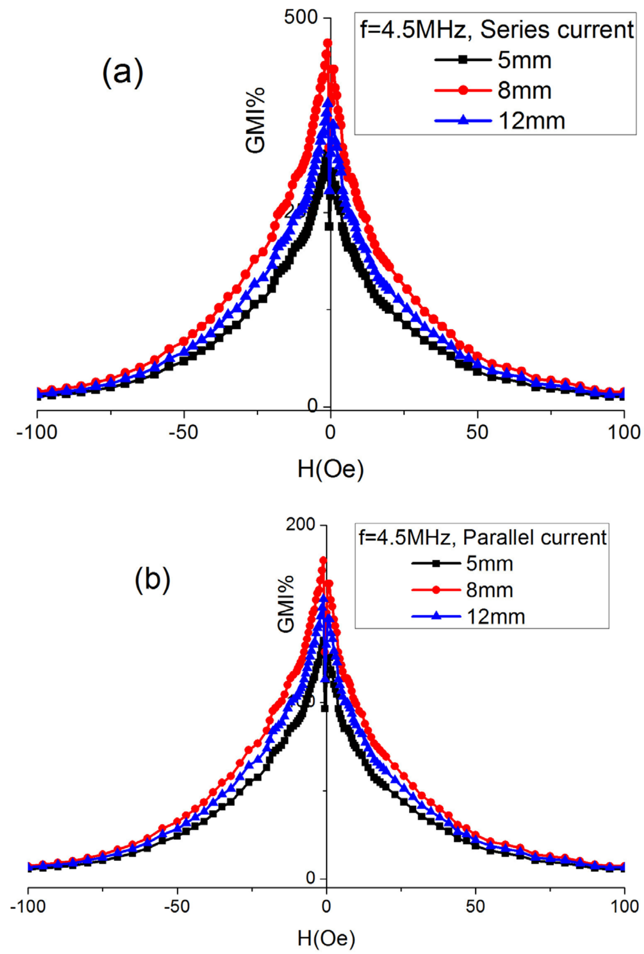

Figure 4. (Color online) GMI profiles of two wires. **(a)** Series. **(b)** Parallel current. at different distances measured at f = 4.5 MHz.

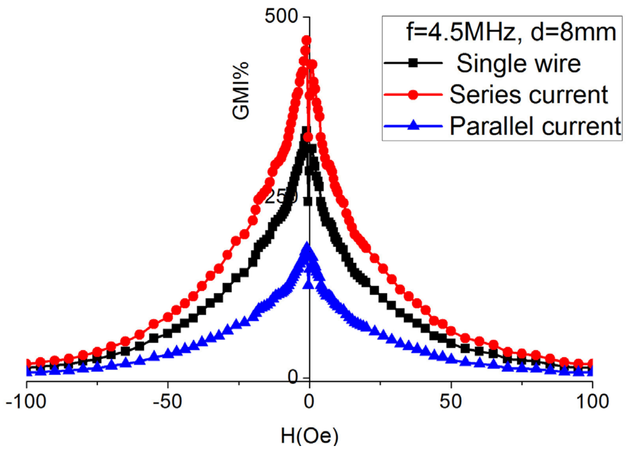

Figure 5. (Color online) GMI profiles of single wire and two wires (series and parallel current with 8 mm distance) measured at f= 4.5 MHz.

To compare the impedance response for single wire and two wires in A_1 and A_2 configurations, of the optimized frequency (4.5 MHz) and the distance of 8 mm is given in Figure 5. According to the obtained results, crossing of current from two parallel wires when series current flows through them leads to an increase in magneto impedance from 340% for single wire to 480% in this case, whereas for crossing of current from two parallel wires when parallel current flows through them leads to a decrease in magneto impedance from 300% for single wire to 180% in this case. We can explain these observations in terms of the stray field and magnetic interactions between the current carrying wires. When the magnetic microwires carrying the current in the opposite direction are placed in close proximity, the effective circular field which is generated due to the wires is strong enough and it can increase the circular magnetization of the system. Interactions of stray fields which are generated by each micro with the applied magnetic field can affect the magnetization of neighboring micro wires. As the applied field affects the low field magnetization of Co-rich micro wires, the stray field which is generated by each Co-rich microwire is magnetic field dependent. The interplay of these factors leads to large circumferential permeability, consequently it increases the GMI ratio. If we increase the distance between them, however, the mutual interaction becomes weaker thereby decreasing the circular magnetization. As a result, the circumferential permeability falls off that diminishes the GMI ratio. With increasing the distance between them, however, the mutual interaction becomes weaker thereby decreasing the circular magnetization. As a result, the circumferential permeability falls off that diminishes the GMI ratio[6,7]. When distance is up to 12 mm, magnetic interaction is weak, and the largest $\Delta Z/Z$ decreases. Then, GMI response could be effectively enhanced via suitable magnetic interaction through controlling the distance of wires.

For A_2 configuration when the magnetic micro wires are placed in close proximity and carry the current in the same direction, the effective circular field generated due to the wires is not strong enough to increase the circular magnetization of the system. Such an interpretation has also been mentioned for the amorphous micro wires with nominal composition of $Co_{68}Fe_{4.5}Si_{15}B_{12.5}$ with diameter of around 32 μm[7] and $Co_{68}B_{15}Si_{10}Mn_7$[6]. In order to make a direct comparison, seven sets of data are exposed in Table 1.

Using Equation (3), sensitivity was calculated for different frequencies and distances (Table 1). As can be seen, for all three frequencies and distances, sensitivity has increased and decreased, respectively for A_1 and A_2 configuration compared with the single wire. It can be found that a significant increase of $\Delta Z/Z$ is observed

Table 1. GMI ratio (%) and dc magnetic field sensitivity (1/Oe) for single wire and two wires (A_1 and A_2 configuration). The maximum values of the GMI ratio was measured for driving current with 14 mA and 4.5 MHz frequency

Different configurations	Distance (mm)	Frequency (2 MHz)		Frequency (4.5 MHz)		Frequency (6 MHz)	
		Sensitivity	GMI	Sensitivity	GMI	Sensitivity	GMI
Single wire	-	20.6	237	22.1	342	21.6	314
A_1	5	21.3	277	23.2	363	22.7	326
A_1	8	37.1	350	41.2	483	35.9	467
A_1	12	27.0	284	31.4	392	26.1	378
A_2	5	10.7	134	12.2	202	10.2	184
A_2	8	8.8	125	8.7	175	8.7	161
A_2	12	12.5	138	13.1	197	11.6	192

when two quasi-identical wires are arranged in parallel mode with series current (A_1 configuration), which indicates that the parallel connection with series current is an effective method of improving GMI property for potential sensor application.

4. Conclusion

The parallel setup of two wires can change the giant magneto impedance response. It was shown that the role of the current type in two wires is critical. Depending on the setup in series or parallel current for two wires can increase or decrease the GMI effect. Under suitable conditions, considerable enhancement in the GMI can be achieved by this technique. The best condition for GMI response measured in series current type and 8 mm distance between two wires. In this type the impedance ratio increases from 340% of single wire to 480% in series current type. In parallel current mode, the GMI effect was reduced in all distances and conditions. For instance the GMI ratio decreases to 180%.

5. References

1. Ripka P. Magnetic sensors and magnetometers. Measurement Science and Technology. 2002; 13(4):645.
2. Panina LV, Mohri K. Magneto-impedance effect in amorphous wires. Applied Physics Letters. 1994; 65(9):1189–91.
3. Knobel M, Sanchez ML, Gomez-Polo C, Marin P, Vazquez M, Hernando A. Giant magneto-impedance effect in nanostructured magnetic wires. Journal of Applied Physics. 1996; 79(3):1646–8.
4. Mardani R, Amirabadizadeh A, Ghanaatshoar M. Angular dependence of giant magneto impedance and magnetic characteristic of Co-based wire in different magnetic field ranges. Modern Physics Letters B. 2014; 28(25).
5. Sivachidambaranathan V. High frequency isolated series parallel resonant converter. Indian Journal of Science and Technology. 2015; 8(15).
6. Devkota J, Ruiz A, Mukherjee P, Srikanth H, Phan MH, Zhukov A, Larin VS. Magneto-resistance, magneto-reactance, and magneto-impedance effects in single and multi-wire systems. Journal of Alloys Compounds. 2013; 549:295–302.
7. Zhang SL, Chai YS, Fang DQ, Wang LC, Xing DW, Sun JF. Giant magneto-impedance effect of two paralleled amorphous microwires. Rare Metals. 2014; 1–5.
8. Fan J, Wu J, Ning N, Chiriac H, Li X P. Magnetic dynamic interaction in amorphous microwire array. IEEE Transactions on Magnetics. 2010; 46(6):2431–34.
9. Garcia C, Zhukova V, Zhukov A, Usov N, Ipatov M, Gonzalez J, Blanco JM. Effect of interaction on GMI effect in a system of few thin wires. Sensors Letters. 2007; 5(1-3):10–2.
10. Phan MH, Peng HX, Yu SC, Wisnom MR. Large enhancement of GMI effect in polymer composites containing Co-based ferromagnetic microwires. Journal of Magnetism Magnetic Materials. 2007; 316(2):253–6.
11. Chiriac H, Herea DD, Corodeanu S. Microwire array for giant magneto-impedance detection of magnetic particles for biosensor prototype. Journal of Magnetism Magnetic Materials. 2007; 311(1):425–8.
12. Mardani R, Amirabadizadeh A, Ghanaatshoar M, Farsi H. The influence of magnetic field direction and amplitude in direct current-field annealing on the magnetoimpedance of Co-based wires. Journal of Superconductivity Novel Magnetism. 2015; 28(8):2441–6.