Giant magnetoimpedance in layered composite micro-wires for high-sensitivity magnetic sensor applications

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Abstract. Currently, the design and development of novel magnetic materials with optimized properties is of relevance to study new phenomena and to use them for multifunctional applications of sensor technologies and magnetoelectronic devices. In this letter, we present a detailed investigation of giant magnetoimpedance (GMI) effect in layered magnetic microwires. A new family of layered microwire composite materials was fabricated by using rapidly quenching and coating techniques. The experimental measurements were performed using an impedance analyzer (HP 4191A) in the frequency range of 100 – 1000 MHz and a varying applied dc magnetic field within ± 300 Oe. Interestingly, the GMI ratio and magnetic-field sensitivity reached the largest values of 3200 and 2400%/Oe at a resonance frequency of 890.15 MHz for layered Co-rich microwire sample, respectively. These results are very ideal for the development of a new family of ultra-sensitive and high-frequency magnetic sensors. Finally, the layered composite magnetic micro-wire developed with enhanced sensitivity performance can be ideally used as sensing elements in magnetic sensor technologies.

Keywords: Giant magnetoimpedance, layered magnetic microwires, magnetic sensor.

1. Introduction
Nowadays, high-performance sensors and transducers have an increasing interest in the society, industry and academia, because of their importance in many technological applications [1]. All modern vehicles and transport means use a vast variety of sensors and transducers. The operation of all medical instruments is also based on sensors and transducers. Industry is also employing more and more transducers for the monitoring and control of production lines [2].

A recent discovery of giant magneto-impedance (GMI) effect in amorphous magnetic wires [3] has given rise to a new direction in magnetic sensor technology. These soft magnetic wires exhibited outstanding properties such as: (i) relatively high resistivity, (ii) tiny dimensions, (iii) high permeability (or low coercivity), and (v) increased mechanical strength. With these excellent properties, these wires are to be promising candidate for micro-technological applications, and present an attractive option for high-sensitivity magnetic sensors, advanced measurement and control systems, and high-density magnetic recording applications [4, 5].

In the present work, a new class of layered composite micro-wires was designed and fabricated by using rapidly quenching and coating techniques. A detailed investigation of the high-frequency GMI behaviours in these materials was performed. It has been revealed that the layered composite magnetic
micro-wire developed with enhanced sensitivity performance ideally represents a new class of sensing materials with great technological potential in high-sensitivity sensor devices.

2. Experimental works

Figure 1 shows the schematic view of fabrication process and composite micro-wire sample. The inner ferromagnetic core is a Co-rich microwire of nominal compositions Co$_{83.2}$B$_{3.3}$Si$_{5.9}$Mn$_{7.6}$ fabricated by Taylor-Ulitovsky method [6], in which the alloy pieces were previously introduced in a glass tube having a sealed end, and then the alloy was melted by the high frequency field of an inductive coil and the end of the glass tube was softened. Hence, around the molten metal drop, there was a softened glass cover which allows the drawing of the capillary. The glass tube displaced with a uniform speed ranging between 0.5 and 7 mm/min in order to ensure the continuity of the process. The as-formed wire was cooled by a water jet at approximately 1 cm under the high frequency induction coil. The diameter of the ferromagnetic core was about 16 $\mu$m and the thickness of the insulating glass coating was about 5 $\mu$m. The prepared microwire sample of 15 mm in length was fixed on a glass substrate. A conductive layer with 0.5 $\mu$m in thickness was deposited on the glass-coated micro-wire at two ends of the microwire by coating technique. And then, two copper contact terminals of 10 mm in length were connected with the sample.

![Image](b)

**Figure 1.** a) A schematic view of Taylor-Ulitovsky method (above, left side) for fabrication of amorphous composite micro-wire (below, left side); b) A layered composite micro-wire (right side) consists of a,b: Co-rich ferromagnetic core; c,d: conductive layers; e: glass coating.

The impedance values of all investigated samples were directly measured by an impedance analyzer (HP4191A, 1 MHz – 1 GHz) in a wide frequency range from 100 - 1000 MHz. During the measurement, the power of the output terminal in HP4191A was fixed as 1 mW. Therefore, the current amplitude was varied as a function of frequency and also abruptly changed at near the resonance point. Impedance measurements were conducted along the sample axis under a longitudinal applied dc magnetic field. The external dc magnetic field, created by a solenoid, was swept through the entire cycle equally divided by 800 intervals from -300 to +300 Oe.

The percentage change of magnetoimpedance, e.g. GMI ratio, with applied dc magnetic field has been expressed as [7]

$$\text{GMI (\%)} = \frac{\Delta Z/Z}{\%} = 100 \% \times \left[ \frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})} \right], \quad (1)$$

and the dc magnetic-field sensitivity of GMI as

$$\xi = \frac{\Delta Z/Z(\%)}{\Delta H}, \quad (2)$$

where $H_{\text{max}}$ is an applied maximum dc magnetic field and $H_{\text{max}} = 300$ Oe in the present work. $\Delta H$ stands for the full width at half maximum (FWHM).
3. Results and discussion

From the fundamental point of view, the GMI can be understood as a large change in the alternating current (ac) impedance of a magnetic conductor with an ac when subjected to a dc magnetic field. It originates from the skin effect as a consequence of the changes in the penetration depth ($\delta_m$) induced by the applied dc magnetic field through modification of the effective permeability of a magnetic material [8]. This change of the penetration depth, for example, for a magnetic wire, can be described by formula

$$\delta_m = \sqrt[2]{\frac{\rho}{2\pi f\mu_\phi}},$$

where $f$ is the frequency of the ac current flowing along the sample, $\rho$ is the electrical resistivity, and $\mu_\phi$ is the circumferential magnetic permeability [9]. Since application of a dc magnetic field increases the skin depth and thereby decreases the impedance, the penetration depth should be as small as possible in the absence of an applied magnetic field, in order to obtain a GMI effect. It reveals that the GMI effect would exist in materials having (i) low resistivity, (ii) high effective permeability, and (iii) low relaxation parameter [10]. In this context, Co-rich amorphous wires are good candidates for GMI sensor applications, because they possess extremely high circumferential permeability arising from their circumferential domain structure [9, 10]. The GMI characterizations are strongly dependent on the frequency of the ac current flowing along the sample and the applied magnetic field. We will analyze these dependences in detail.

Figure 2. The field-dependent GMI curves for layered Co-rich composite micro-wire measured at different frequencies of a) 385 MHz; b) 519 MHz; c) 740 MHz; and d) 890 MHz.
3.1. **Driving frequency dependence of GMI**

Figure 2 displays the field-dependent GMI curves measured at different frequencies. It can be easily seen that the shape of GMI curves varies dramatically as the frequency increases. GMI profiles show a single-peak feature, or a double-peak one, depending upon a certain frequency region. According to the GMI theory [8], at high frequencies (1 MHz $< f < 1$ GHz), the GMI effect was ascribed to variations of the magnetic penetration depth due to strong changes of the effective permeability caused by an applied dc magnetic field. In this case, both domain walls motion and magnetization rotation contribute to the circular permeability and consequently to the GMI effect. In our present case, because the measuring frequency varies from 100 – 1000 MHz, consequently, the observed GMI behavior was mainly related to the rotation of magnetic moments arising from the circular magnetization process. In the investigated frequency range, large GMI ratio values of 900% and 1500% were found at measuring frequencies of 519 and 890 MHz, respectively, as shown in figure 2b and 2d. These results make the layered wire-shaped material very ideally for developing high-sensitivity magnetic sensor applications.

![Figure 3. The field-dependent GMI curve measured at 890.15 MHz.](image)

3.2. **Magnetic field dependence of GMI**

To measure GMI effect, a dc magnetic field is usually applied parallel to the ac current along the longitudinal direction of the sample [8, 9]. At a given frequency, the application of a dc magnetic field ($H_{dc}$) changes the circumferential permeability $\mu_\phi$ and hence the penetration depth $\delta$ which in turn alters the magnetoimpedance until the value of $\delta$ reaches the radius of the sample ($a$). To achieve a large GMI effect the penetration depth should be as small as possible in the absence of an applied magnetic field. Large circumferential permeability along with a low value of the resistivity gives rise to a small penetration depth at high frequency range. A large increase of the circumferential permeability can be achieved by applying an ac current of the frequency sufficiently high to excite the resonance of the sample. This large circumferential permeability at the resonance strongly decreases the penetration depth and, therefore increases the impedance of the sample. As observed in figure 2, it is worth noting that, at the resonance frequency of 890 MHz, the maximum GMI value is much larger than that obtained at 519 MHz. This implies that the resonance at 890 MHz produced a larger circumferential permeability when compared to that at 519 MHz. This hypothesis can be acceptable because the ferromagnetic resonance actually occurs around 890 MHz ($\sim 1$ GHz) resulting in an increase of the permeability with respect to frequency. Therefore, a smaller dc magnetic field is required to excite the sample at 890 MHz and a larger GMI effect is consequently observed. This probably explains a shift of the position of the resonance peaks towards lower values of the applied field, when the resonance frequency increases from 519 to 890 MHz. As one can see from figure 2d
and 2d, at the frequency of 519 MHz, the resonance peaks appear at $H_{dc} = \pm 24.6$ Oe, whereas it occurs at $H_{dc} = \pm 12.3$ Oe at the frequency of 890 MHz.

In order to further improve the GMI sensitivity, we investigate the GMI behavior around the resonance frequency of 890 MHz. It is noted that from the magnetic field dependence of GMI we can calculate the field sensitivity of GMI $\xi$ (%/Oe) as illustrated by equation (2). In practice, based upon the magnitude of $\xi$, the operating regime and potential applications of a magnetic material can be determined. Interestingly, the largest GMI value of 3200 % was observed at a measuring frequency of 890.15 MHz (figure 3). The field sensitivity of GMI calculated is about 2400 %/Oe. This is one of the highest values of field sensitivity of GMI reported till now in the research of GMI. These results are very ideal for developing ultra-sensitive magnetic sensors operating at the high-frequency region.

4. Conclusion

In the present work, a new class of layered Co-rich composite micro-wire was fabricated by the two-step process including rapid quenching and coating. A study of high-frequency GMI behavior in newly layered composite micro-wire was performed. Noticeably, the GMI effect was observed at two frequencies of 519 MHz and 890 MHz. Very interestingly, the largest field sensitivity of GMI reached a large value of 2400 %/Oe at a measuring frequency of 890.15 MHz. These results revealed that the layered material can be used as a sensing element for high-performance sensor devices.

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