MAGNETOIMPEDANCE HYSTERESIS EFFECTS IN AMORPHOUS GLASS-COATED MICROWIRES FOR EMBEDDED SENSING APPLICATIONS

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ABSTRACT

During the last two decades, ferromagnetic materials have appealed much attention due to their lenient magnetic properties and enhanced electrical resistivity, which is helpful to implement in various industrial sensing applications. Recently, amorphous glass-coated microwires have become available, combining mild magnetic properties with specific magnetic anisotropy. The magnetic hysteresis loops and magnetoimpedance effects in C-rich microwires covered with glass have been investigated in the present work. This largely depends on the sign of the magnetostriction saturation. Such behaviors were demonstrated in wires of the identical composition Co71Fe5B11Si10Cr3 but with dissimilar geometric properties. Depending on the easy anisotropy direction, the wire can exhibit such unique properties as magnetic bistability (magnetization changes abruptly between the two stable states), wall propagation, and giant magnetoimpedance. Furthermore, the wires can be further subjected to internal tensile stress to realize stress-sensitive magnetostriction, which can be proposed in embedded sensing sensors.

Keywords: Ferromagnetic microwires; Taylor-Ulitovsky method; Magnetoimpedance effects; Embedded stress sensors.

1. INTRODUCTION

Over the past few decades, the field of magnetism has changed our understanding tremendously due to its remarkable properties. Previously, scientists used to study and characterize soft magnetic materials to adjust the effectiveness of their magnetic attributes and the cost. However, the modern society of soft magnetic materials has recently taken us in a new direction towards the advancement in the field of applied physics, technologies, material sciences, and much more [1-4]. Therefore, thin wires from modern magnetic materials have received all the attention, and amorphous ferro-magnetic type glass-coated microwires are one of them. These microwires got more attention because of their reduced geometrical dimensions, enhanced soft magnetic properties, giant magneto-impedance (GMI) impact, Barkhausen impact (LBE), and other excellent properties [5-6]. Previously, ferromagnetic microwires were prepared by various methods. For example, I.S. Miroshnitchenko accompanying I.V. Salli produced the first metallic glass nearly 50 years ago by swift stimulating from the liquid state and later by P. Duwez et al. [1], [7]. But amorphous glass-coated microwires have a unique place in the modern world. The Amorphous glass-coated microwires are obtained by the Tailor-Ulitovsky procedure available in a range of metallic diameters from 1- 20 mm, which cannot be obtained using the old quenching method due to the high surface energy of the liquid metal [8-9]. In the Taylor technique, latterly known as the microwire process or Taylor-wire, different metals and alloys have been used to produce a variety of microwires with core diameters for various applications. This technique is relatively inexpensive compared with other old methods, therefore, it received more attention in making these wires.

Especially in-embedded sensing procedure/ method, some special fillers are required, which can behave as mediators between the internal factors/parameters of the given medium as well as a readout device. Based on the physical attributes of this transitional function, different quantities, physically, can be achieved as the measurement factors, which include: complex permittivity, voltage, impedance, current, and resistance and electric-magnetic fields [10-12]. Therefore, conducting a comparative analysis of microwires' magnetic properties and MI effects with different geometrical configurations would be beneficial and can be used in embedded sensing applications.

Developing wireless magnetic sensing materials with small size and improved performance are progressively critical for several applications, especially embedded sensors. Therefore, we need to investigate of magnetic properties of micron-sized amorphous ferromagnetic wires to tackle this problem. The present work studies the magnetic hysteresis (M-H) loops and magnetoimpedance (MI) effects of the same chemical composition alloy glass-coated microwires. Particular prominence is given to seeing the impact of dissimilar geometrical configurations on their properties. Furthermore, the correlation between magnetic hysteresis (M-H) loops and magnetoimpedance (MI) results is discussed. The wire sample composition is taken as Co71Fe5B11Si10Cr3 with two different geometries having total wire diameters of sample No. (1): 41.5 microns and sample No. (2): 29.5 microns ensuring small and positive magnetostriction. Our conducted experiments are premeditated not only to determine the effect of the physical properties of microwires but also to address the direct relation of wires' geometrical relationship with the sensitivity that is related to the embedded sensors.

2. MATERIALS AND EXPERIMENTAL DETAILS

2.1 Fabrication of Amorphous Glass-coated Microwires

The most recent fabrication procedure to fabricate glass-coated microwires is the Modern Taylor-Ulitovsky method [13-14]. The wires made by this technique usually have a uniform coating of insulating glass attached closely to the metallic core [7]. The good thing about this technique is that it allows controlling the microstructure and the geometrical structure of the wires. Through this, according to required applications, we can easily regulate the size, such as the nucleus diameter and/or the glass coating thickness.

In the present investigation, the amorphous glass-coated microwires are manufactured through a modern Taylor–Ulitovsky method [13]. This technique is based on the direct casting of wires from the melting of alloy, as schematically shown in Figure 1. First, a limited grams of quantity for master alloy with the anticipated composition, i.e., $Co_{71}Fe_5B_{11}Si_{10}Cr_3$ are placed into a Pyrex-like glass tube and located within a high-frequency inductor heater. Next, the alloy is heated up to its melting point to let it form a droplet. While the metal melts forcing the portion of the glass tube which is adjacent to the melting metal, to soften, enveloping the metal droplet. Finally, a glass capillary is drawn carefully from the softened glass portion and wound on a rotating coil, as shown in Fig. 1. At appropriate drawing conditions, a microwire is thus formed where a glass shell completely coats the metal core. Thus, microwires with two different diameters were fabricated and their detailed configurations are provided in Table 1.

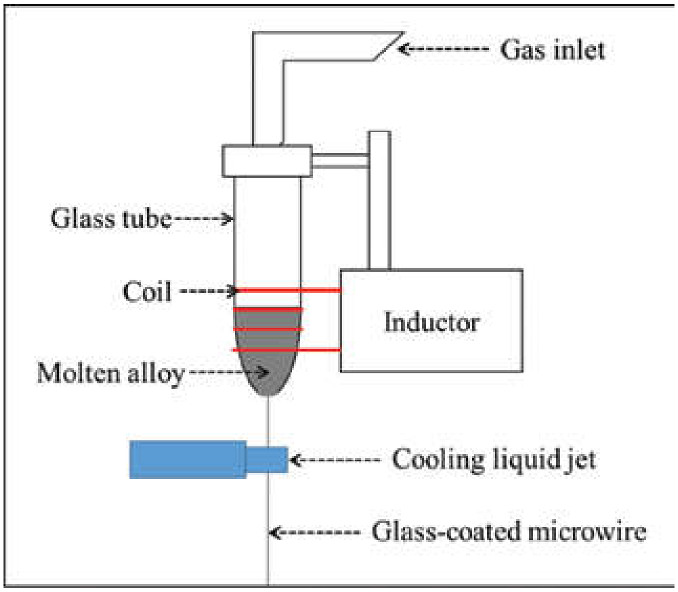

Figure 1: Schematic diagram of fabrication of glass-coated microwires by Taylor-Ulitovsky method.

However, in the production methodology of these wires, some components are often generated, such as internal stress with radial, axial or circular [2], [15], [16]. This is because they are developed inside the metallic part of the wire, and these factors arose due to the different quenching rates. These rates lie between the microwires' central region and the upper surface layer. Moreover, the induced stress in the prepared microwires is generated due to the alteration in their thermal expansion coefficients, which can be either due to the metallic nucleus or the glass layer. This effect plays a vital role in microwires [1], [17].

2.2 Characterizations

A field emanation scanning electron microscope (SEM, Hitachi) was employed to observe the morphologies of the as-prepared microwires. Amorphous ferromagnetic microwires are generally influenced by the magnetostriction coefficient, s, and by the strength of internal stress, ρ, which are generated by glass-coating influenced by the ρ -ratio of the diameter of the metallic core, d, to the total diameter of microwire, D ($\rho = d/D$). The experimental magnetization arcs were obtained by an inductive methodology with a set of two differential coils. The magnetization coils were agitated by a current of 500 Hz producing a magnetizing field having an amplitude of 1000 A/m. The persuaded voltage vs time was alphanumerically integrated to acquire a hysteresis loop. The short-cut wire was then inserted into a slender detection coil with an internal diameter of 3 mm and a span of 5 mm.

The magnetoimpedance effects in the wires are demonstrated with the help of Vector Network Analyzer (Model: Hewlett-Packard 8753E) for frequencies ranging from 1-100 MHz by measuring the S21/S12-parameters having forward transmission coefficient for specially designed microwave stripe-cell with a microwire. First, we placed a single piece of microwire having a length of 6 mm in a specially developed microstrip sample holder, which is placed within an extended solenoid that produces a homogeneous magnetic field to the range up to 15 KA/m alongside the micro-wire axis. Then, we determined the longitudinal impedance $Z\phi z$ using VNA from the reflection transmission coefficient S22/S11 measurement, and the off-diagonal impedance dignified from the S12/S21 as a voltage is induced in a pick-up coil of 2 mm long wounded over a microwire.

3. RESULTS AND DISCUSSION

3.1 Morphology, Compositional Characteristics of Microwire Samples

The particulars of the chemical composition and geometric dimensions of the premeditated microwires are offered in Table 1. Two different types are used to study their magnetic and MI properties.

Table 1: The as-prepared microwire's composition with their inner and outer diameters.

Alloy Composition	Inner Diameter (μm)	Outer Diameter (μm)
$Co_{71}Fe_5B_{11}Si_{10}Cr_3$	36.5 microns	41.5 microns
$Co_{71}Fe_5B_{11}Si_{10}Cr_3$	23.9 microns	29.5 microns

To examine the surface morphologies of the as-prepared microwires, the wires were subjected to chemical etching by the diluted hydrofluoric (HF) acid solution to dissolve the glass layer. As a result, the surface of the as-prepared wires (Fig. 2(a-d)) exhibits some in-homogeneities instigated by the interaction between the metallic nucleus and glass layer throughout the casting process [18-19]. In addition, thermally induced surface defects for both wire samples can be observed probably due to heating inhomogeneity during the casting process. However, microwires, in general, recollect their integrity after fabricating. The hysteresis loops

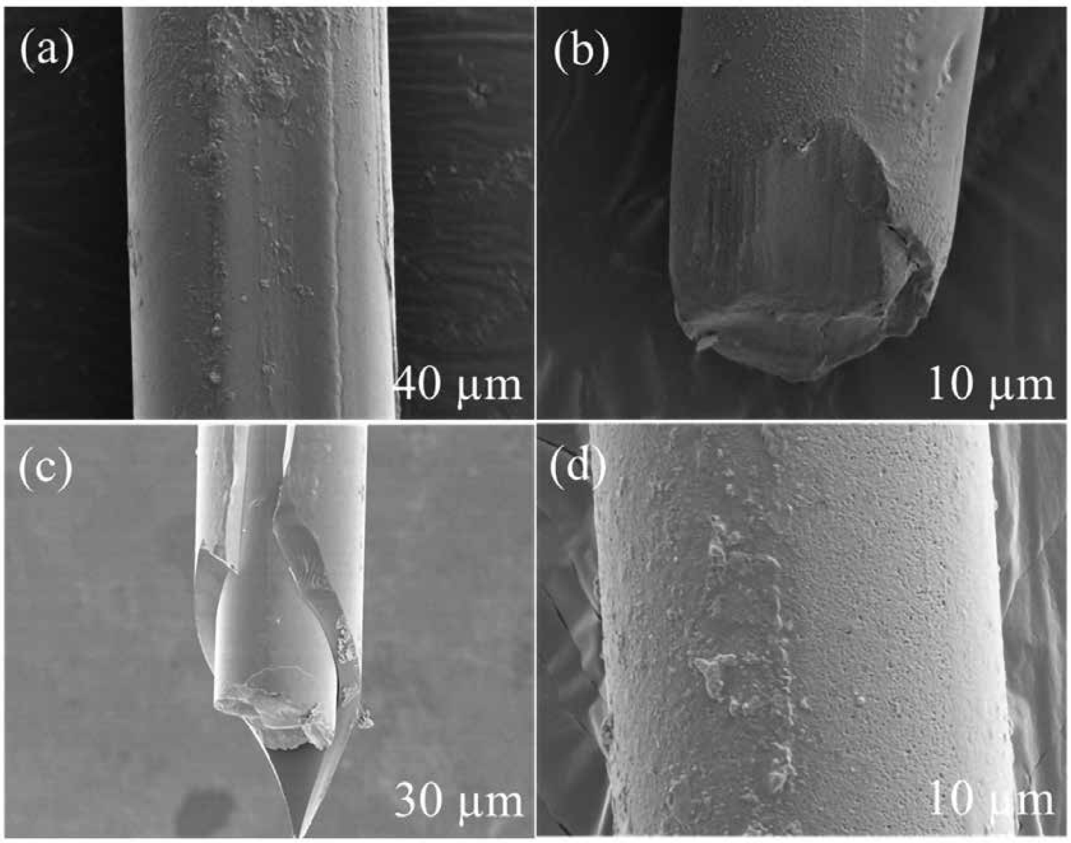

Figure 2: SEM images of the Co71Fe5B11Si10Cr3 microwires with different inner and outer diameters, i.e., (a, b) 36.5 microns and 41.5 microns; and (c, d) 23.9 microns and 29.5 microns, respectively.

3.2 Hysteresis Loop of as-prepared Wires

Amorphous glass-coated microwires of $Co_{71}Fe_5B_{11}Si_{10}Cr_3$ chemical composition with a slight positive magnetostriction constant of the order of 10-7 have been studied. Two types of wires with different structural geometrical parameters were used, labeled as sample No. (1) and Samples No. (2), as discussed in detail in Table 1.

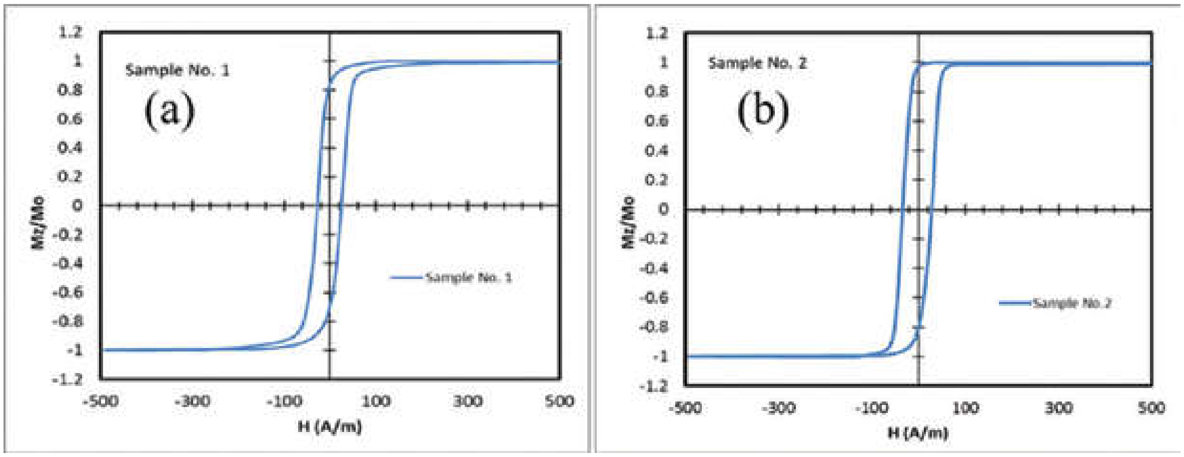

Figure 3: Experimental hysteresis loops for $Co_{71}Fe_5B_{11}Si_{10}Cr_3$ microwires with different diameters i.e., (a) 41.5 μm and (b) 29.5 μm, respectively.

are almost identical for both types of wires, with a small coercitivity of about 25 A/m, as shown in Fig. 3(a, b). However, the hysteresis loop for the wire with a smaller diameter (Sample No. (2)) has a more pronounced bi-stable behavior. In addition, the remanence value close to the saturation also confirms the existence of the axial anisotropy almost in the entire wire.

3.3 Magneto-impedance (MI) effect behavior of as-prepared Microwires

Comparing the behavior of MI in both types of wire samples is interesting since this can give a complete view of the characteristics of changing the anisotropy. Fig. 4(a, b) demonstrate that the MI effect is consistent with the impedance plots, which have a single maximum at zero external fields. Such behavior of MI is typical of materials with an easy anisotropy axis parallel to the magnetic field and excitation current [20]. Furthermore, both wire samples have MI characteristics with one central peak, as shown in Fig. 4(a, b), which also indicates the presence of an axial magnetic field [21-23]. However, the sample of a smaller diameter, i.e., Sample No. (2), has a more sensitive MI with a sensitivity of about 4.5 % per A/m at 100 MHz. In contrast, the MI sensitivity in the second wire is 1.7% per A/m.

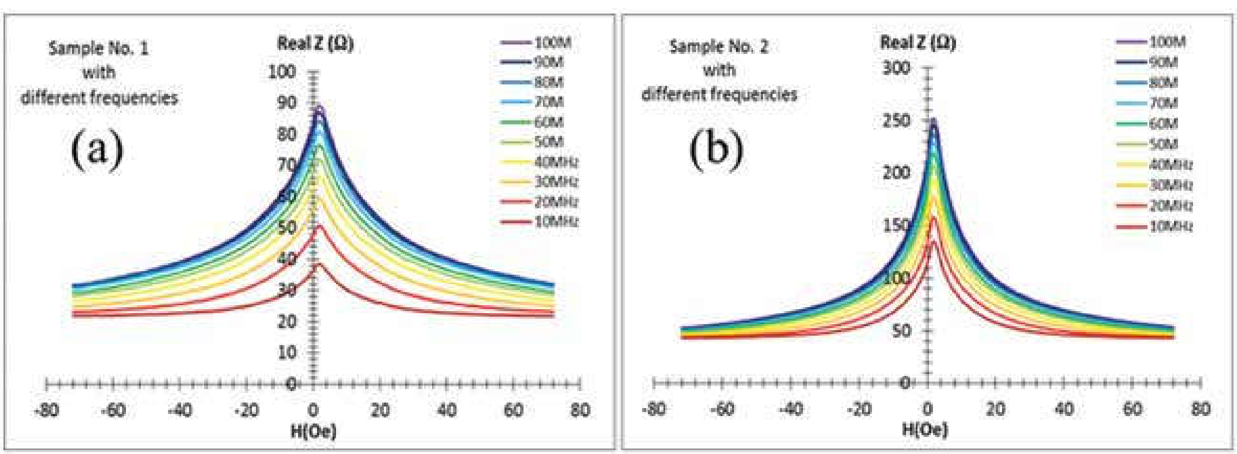

Figure 4: Real part of impedance vs. magnetic field at different frequencies for as-prepared wires with different diameters, i.e., (a) 41.5 μm and (b) 29.5 μm, respectively.

This property resembles the giant magnetoresistance (GMR). It is used for designing sensitive magnetic sensors for shallow magnetic field detection and can be used as embedded sensors, which operate at GHz frequencies [10]. In this case, the primary factor determining the sensitivity is related to the interplay of the wire's dimensions, the chemical composition, and reduced anisotropy [20], [24]. Therefore, the effects in wires observed can be promising for designing miniature built-in embedded sensors.

4. CONCLUSION

In this work, we fabricate the slightly positive magnetostrictive amorphous glass-coated microwires for stress-sensitive embedded sensor applications. We investigated the magnetic hysteresis loops and magnetoimpedance processes in two different types of wires of the same composition $Co_{71}Fe_5B_{11}Si_{10}Cr_3$, with different geometries. We demonstrated that sample No. (2) has a more sensitive MI with a sensitivity of about 4.5 % per A/m at 100 MHz, whereas the MI sensitivity in sample No. (1) is 1.7% per A/m. The sensitivity of the MI effect due to the difference in geometries is proposed to utilize in embedded sensors. Thus, Samples No. (2) can be used in sensing applications. Furthermore, the stress sensitivity of the ratio of harmonics amplitude could also be proposed for practical use to avoid the need for calibration. However, further investigations are carried out to explore new innovative lines for amorphous glass-coated microwires.

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REFERENCES

[1] A. Zhukov, "Novel Functional Magnetic Materials," Springer Ser. Mater. Sci., vol. 231, pp. 1–446, 2017.

[2] M. Vázquez and A. Hernando, “A soft magnetic wire for sensor applications,” J. Phys. D. Appl. Phys., vol. 29, no. 4, pp. 939–949, 1996.

[3] H. García-Miquel, M. J. Esbrí, J. M. Andreés, J. M. García, J. M. García-Beneytez, and M. Vázquez, “Power absorption and ferromagnetic resonance in Co-rich metallic glasses,” IEEE Trans. Magn., vol. 37, no. 1, pp. 561–564, 2001.

[4] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microw. Theory Tech., vol. 47, no. 11, pp. 2075–2084, 1999.

[5] X. Wang, R.-W. Li, C. Chang, A. He, Q. Man, and D. Estévez, “Magnetoinductance and magnetoimpedance response of Co-based multi-wire arrays,” J. Magn. Magn. Mater., vol. 393, pp. 278–283, 2015.

[6] V. Zhukova, M. Ipatov, J. González, J. M. Blanco, and A. P. Zhukov, "Development of thin microwires with enhanced magnetic softness and GMI," IEEE Trans. Magn., vol. 44, no. 11 PART 2, pp. 3958–3961, 2008.

[7] H. Chiriac and T. A. Óvári, Amorphous glass-covered magnetic wires: Preparation, properties, applications, vol. 40, no. 5. Progress in Materials Science, 1996.

[8] A. Zhukov et al., "Correlation of crystalline structure with magnetic and transport properties of glass-coated microwires," Crystals, vol. 7, no. 2, 2017.

[9] V. Zhukova, J. M. Blanco, M. Ipatov, M. Churyukanova, S. Taskaev, and A. Zhukov, "Tailoring of magnetoimpedance effect and magnetic softness of Fe-rich glass-coated microwires by stress-annealing," Sci. Rep., vol. 8, no. 1, pp. 1–14, 2018.

[10] D. Makhnovskiy, V. Zamorovskii, and J. Summerscales, "Embedded ferromagnetic microwires for monitoring tensile stress in polymeric materials," Compos. Part A Appl. Sci. Manuf., vol. 61, pp. 216–223, 2014.

[11] J. Olivera, M. González, J. V. Fuente, R. Varga, A. Zhukov, and J. J. Anaya, "An embedded stress sensor for concrete SHM based on amorphous ferromagnetic microwires," Sensors (Switzerland), vol. 14, no. 11, pp. 19963–19978, 2014.

[12] A. Allue et al., "Smart composites with embedded magnetic microwire inclusions allowing non-contact stresses and temperature monitoring," Compos. Part A Appl. Sci. Manuf., vol. 120, no. January, pp. 12–20, 2019.

[13] V. S. Larin, A. V Torcunov, A. Zhukov, M. Vazquez, and L. Panina, "Preparation and properties of glass-coated microwires," J. Magn. Magn. Mater., vol. 249, pp. 39–45, 2002.

[14] H. Chiriac, "Preparation and characterization of glass covered magnetic wires," Mater. Sci. Eng. A, vol. 304–306, no. 1–2, pp. 166–171, May 2001.

[15] P. Klein, R. Varga, G. Infante, and M. Vázquez, "Ferromagnetic resonance study of FeCoMoB microwires during devitrification process," J. Appl. Phys., vol. 111, no. 5, 2012.

[16] M. G. Nematov et al., "Effect of Mechanical Stresses and Annealing on the Magnetic Structure and the Magnetic Impedance of Amorphous CoFeSiBCr Microwires," Phys. Solid State, vol. 60, no. 2, pp. 328–333, 2018.

[17] I. Liberal, I. S. Nefedov, I. Ederra, R. Gonzalo, and S. A. Tretyakov, "Electromagnetic response and homogenization of grids of ferromagnetic microwires," J. Appl. Phys., vol. 110, no. 064909, pp. 1–8, 2011.

[18] M. Vázquez, H. Chiriac, A. Zhukov, L. Panina, and T. Uchiyama, "On the state-of-the-art in magnetic microwires and expected trends for scientific and technological studies," Phys. Status Solidi Appl. Mater. Sci., vol. 208, no. 3, pp. 493–501, 2011.

[19] H. Lu, V. Zhukova, M. Ipatov, A. Zhukov, W. Wan, and Y. Shen, "Surface defect detection of magnetic microwires by miniature rotatable robot inside SEM," AIP Adv., vol. 6, no. 9, p. 095309, 2016.

[20] A. Uddin et al., "Temperature Effects on the Magnetization and Magnetoimpedance in Ferromagnetic Glass-Covered microwires," in Journal of Physics: Conference Series, 2017, pp. 1–5.

[21] L. Li, M. Zhang, Q. Liao, W. Xia, and X. Ding, "Smart Composites With Short Ferromagnetic Microwires for Microwave Applications Composites With Short Ferromagnetic Microwires for Microwave Applications," IEEE Trans. Magn., vol. 531, no. 10, pp. 18–22, 2012.

[22] L. V. Panina, M. Ipatov, V. Zhukova, A. Zhukov, and J. Gonzalez, "Magnetic field effects in artificial dielectrics with arrays of magnetic wires at microwaves," J. Appl. Phys., vol. 109, no. 5, 2011.

[23] M. M. Salem, M. G. Nematov, A. Uddin, L. V. Panina, M. N. Churyukanova, and A. T. Marchenko, "CoFe-microwires with stress-dependent magnetostriction as embedded sensing elements," J. Phys. Conf. Ser., vol. 903, no. 1, pp. 1–4, 2017.

[24] M. H. Phan and H. X. Peng, "Giant magnetoimpedance materials: Fundamentals and applications," Prog. Mater. Sci., vol. 53, no. 2, pp. 323–420, 2008.