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HIGH-RESOLUTION FLUXGATE SENSING ELEMENTS USING $Co_{68,25}Fe_{4,5}Si_{12,25}B_{15}$ AMORPHOUS MATERIAL

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$Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous magnetic material for the development of high performance fluxgate sensors is investigated. The results refer to the Vacquier-Foerster configuration sensors and direct driving sensors having amorphous ribbons or wires as sensing elements. The main factor that influences the magnetic behaviour of the sensors cores is the heat treatment. The sensor performances depend on both the magnetic behaviour of the cores and the circuitry. The obtained results are discussed in terms of the magnetization processes, which take place in ribbon and wire-based cores. Vacquier – Foerster sensors having good sensitivity (7±0.5) μV / nT, thermal stability of the offset in the temperature range –75 to +25°C (0.04 nT/°C) and reduced magnetic noise level (350 pT) are produced. The possibility to use higher exciting frequencies in the case of direct driven fluxgate sensors leads to an increase of the sensitivity upto 75 μV/nT. Miniature sensors with sensitivity of 20 μV/nT and 40 μV/nT, which can be used for electromagnetic pollution measurements, were manufactured. The possibility to use the developed sensors based on $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous alloys to measure alternating magnetic fields up to 200 μT is demonstrated.

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1. Introduction

The discovery of the soft magnetism in amorphous alloys associated with their glass-forming ability, which makes possible their casting in the form of thin ribbons or wires, created a great stimulus to further researches in order to develop magnetometric sensors based on amorphous materials. The studies accomplished in the last years on the amorphous core sensors [1-4] showed that the low magnetostrictive core materials can significantly contribute to fulfil the technological and metrological requirements imposed to vector field sensors with very high performances, traditionally used for geophysical research, geological and archeological prospecting, materials testing, navigation applications and space researches. These requirements include a good thermostability both for the magnetic noise and for the sensor offset in a large temperature interval as well as a good sensitivity of the sensor. These studies proved that the non-magnetostrictive amorphous ribbons are good competitors for permalloys.

The main tendencies of the magnetic sensors applications refer to the miniaturization, the increase of the sensitivity and the reduction of the sensor magnetic noise level. Although the miniaturization is an advantage of the fluxgate sensors, it has as secondary effect the diminution of the sensor sensitivity. The effect of sensitivity reduction can be compensated by using a higher exciting frequency and/or by choosing suitable solutions in order to reduce the noise level. These two requirements are fulfil by the differentially DC biased magnetic field sensors [5] and direct driven fluxgate sensors [6].

In differentially DC biased fluxgate sensors, the increase of the sensitivity is achieved using the magnetic susceptibility resonance in amorphous core. By suitable choice of the operational point of the resonance curve and adequate DC biased level a reduction of the noise level is obtained [5].

The direct driven fluxgate sensor [6] can be characterized as an extremely simple construction consisting of one coil surrounding a loop-shaped piece of amorphous core. The ferromagnetic core material itself is the carrier of the excitation current. In this type of sensor, the effect of sensitivity reduction caused by miniaturization can be compensated using a higher frequency of the excitation current that flows through the sensor core.

On the other hand, the magnetic properties of amorphous alloys can be tailored by means of inducing additional anisotropies and low noise magnetic field sensors can be obtained. By suitable tensile stress annealing of the amorphous wires and ribbons the usually called "hard core-axis anisotropy" develops. The presence of the magnetic anisotropy with the ribbon or wire axis as a hard axis of magnetization promotes magnetization rotations rather than domain wall movements in the AC magnetization process used in fluxgate sensors [3]. Therefore, the Barkhausen noise in core material, which determines the limits for the sensitivity and accuracy of a sensor, would be reduced.

This paper presents a review of the results obtained in the development of both Vacquier-Foerster type sensors and direct driven fluxgate sensors based on Co-based amorphous materials as sensing elements. Two kinds of Vacquier-Foerster sensors are studied: classical and differential DC biased magnetic field sensors. The measured functional parameters of the developed sensors prove that the $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous ribbons and wires, suitable stress annealed, are able to produce very good quality fluxgate sensing elements.

2. Experimental

$Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous sensing elements as ribbons and wires were obtained in order to develop three types of fluxgate sensors: classical Vacquier-Foerster sensors, Vacquier-Foerster sensors with bias control and direct driven fluxgate sensors.

Amorphous ribbons 1.1 mm wide and 30 μm thick were prepared by rapid quenching from the melt on a rotating copper wheel. The wires with 125 μm diameter were obtained by the in rotating water spinning method. The amorphous state was tested by X-ray diffraction, differential thermal analysis and thermo-magnetic measurements.

In order to find the most suitable stress annealing conditions the core material was exposed to different stress annealing treatments. The heat treatments applied to the amorphous cores, were divided in two steps: pre-annealing at temperatures between 300 and 360°C and duration between ½ and 1h, followed by stress-annealing at a particular temperature and time interval, but with different values of the applied longitudinal stress. We can apply, retain or modify the longitudinal tensile stress between 200 and 620 MPa applied on the sample placed in a furnace which has the maximum temperature variation in the 120 mm long central region less than 5°C during the heating. The system [4] stabilises the temperature with accuracy better than 1°C. The annealing process is performed in a purified Ar atmosphere.

For the testing of the magnetic behaviour of the $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ cores the typical responses of the magnetization curves on different stress annealing conditions were illustrated for ribbons and wires. The hysteresis loops were obtained by means of a conventional induction method [7]. The samples (ribbons or wires) were driven into saturation with a sinusoidal current waveform; the measurements were performed at 0.5, 1, 5, 10.3, 17 and 20.6 kHz. The measurements of the axial AC hysteresis loops of the ribbons and wires, performed at room temperature, after each heat treatment, allowed us to choose the samples having the most favourable behaviour for the use as sensor cores.

We developed Vacquier-Foerster type sensors similar to the TFS-3 sensors [8], magnetic field sensors with bias control [9], and direct driven fluxgate sensors [10]. Depending on the type of sensor, the measurements of main functional parameters were performed in a pulse excitation field with a maximum value of 650 $A \cdot m^{-1}$ and frequencies in the range 20.6 kHz – 1 MHz and. The sensitivity, the offset and the temperature drift of the offset were determined from transfer characteristics of the sensors in the field range of ± 200 nT at different temperature between -75°C and +40°C. The magnetic noise level of the sensors was determined from 60s time plots of the magnetometer output with the sensor exposed to a 2.4 nT square waveform magnetic field. The recorded signal represents the noise of the sensor together with the noise of the magnetometer and x-t recorder.

The possibility to use the sensors for the measurement of the low frequency magnetic fields was studied using Fourier spectral analysis. An external AC magnetic field with frequency up to 10 kHz was applied. The output signal from the sensor was measured directly with a digital oscilloscope connected to a computer that performed the Fourier analysis. The possibility to measure higher frequencies magnetic fields up to 200 μT was tested with a device [11] for electromagnetic pollution measurements.

3. Results

The stress annealing conditions significantly affect the magnetic behaviour of the samples. The effect depends both on the pre-annealing temperature and its time (Fig. 1) and the applied longitudinal tensile stress value (Fig. 2). The axial hysteresis loop changes to nearly linear and the coercive field decreases. The susceptibility of the stress annealed core sample is inversely proportional to the stress applied during the annealing process. From the hysteresis loops results that the hard axis of anisotropy develops during the appropriate stress annealing. The greater is the tensile stress the larger is the induced anisotropy (Fig. 2). The pre-annealing appears to be very important because the induced anisotropy increases with the pre-annealing time (Fig. 1).

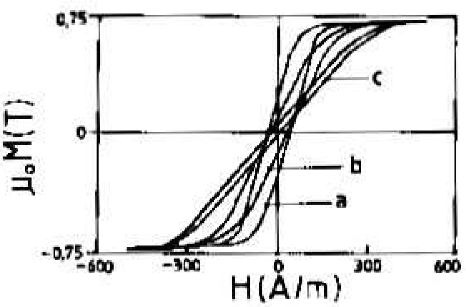

Fig. 1. Axial hysteresis loops for stress annealed (σ = 400 MPa) $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ wires with different annealing temperatures and times: (a) – pre-annealing and stress-annealing for ½h at 300°C; (b) – pre-annealing and stress-annealing for 1h at 320°C; (c) – pre-annealing and stress-annealing for 1h at 340°C. The samples were driven into saturation with a sinusoidal waveform current with frequency of 590 Hz.

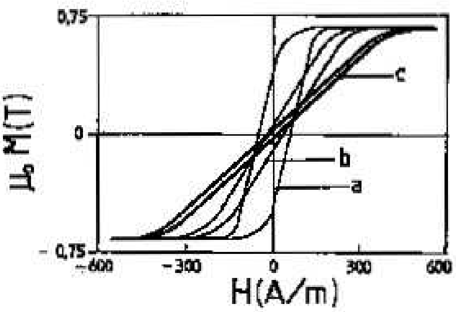

Fig. 2. Axial hysteresis loops for $Co_{68.2}5Fe_{4.5}Si_{12.25}B_{15}$ wires exposed to a pre-annealing for 1h at 320°C followed by stress-annealing for 1h at 320°C with different stress values: (a) as-quenched wire; (b) σ = 400 MPa; (c) (σ = 500 MPa. The samples were driven into saturation with a sinusoidal waveform current with frequency of 590 Hz.

The tensile stress annealing at temperatures between 300 and 400°C applied to the ferromagnetic amorphous core, which in the as-quenched state is characterized by a very low negative magnetostriction constant (λ_s = - 0.08x10^{-6}), results in the change of the sign of the magnetostrictive constant to a small positive value (λ_s = + 0.1x10^{-6}).

The sensors performances depend on the circuitry conditions such as exciting frequency and amplitude of the excitation current as well as the applied heat treatments.

The developed classical Vacquier-Foerster sensors have a sensitivity of (7±0.5) μV/nT, the offset values deviate at most 2 nT from the mean value and the stability of the offset tested in the temperature range -75 - +25°C corresponds to a thermal drift of 0.04 nT/°C. The transfer characteristics of the sensors are symmetrical and linear outside the field range -100 - +100 nT. The temperature variation does not influence the sensitivity values of the sensors. The magnetic noise level of the stress-annealed core sensors, measured in the magnetometer pass-band of 0-10 Hz, remains unchanged between –75 and +25°C and does not exceed 350 pT (p-p). This value is lower than that measured for the as-quenched core sensors, but not as low as we expected. Although these sensors were designed for DC magnetometers, we tested [4, 12] their ability to be used for 0-5 kHz alternating fields measurements at 20.6 kHz excitation frequency. The second harmonic side bands of the fundamental excitation frequency were evaluated from the Fourier spectral analysis of the output signal. The measurements done in AC fields up to 100 μT, in the frequency range 0-5 kHz, evidenced linear transfer characteristics, confirming the capability to measure AC fields in the mentioned ranges.

By developing the differential DC biased magnetic field sensor [9] based on as-quenched $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous ribbons, very good sensitivity (100 ÷ 200 μV/nT) depending on the exciting frequency, a peak-to-peak magnetic noise level lower than that of classical Vaquier-Foerster sensor, were obtained. The work frequency is greater than 102 kHz and the bias magnetic field ranges from 50 to 65 A/m. The linearity range of the sensor response is ±15 μT. The magnetometer equipped with this sensor measures magnetic fields up to 200 μT in the frequency range of 0-10 kHz.

In order to obtain high sensitive miniature sensors, we chosen the solution proposed by Nielsen [6] to develop direct driven fluxgate sensors of different dimensions. With suitable heat-treated amorphous wires (pre-annealed 1h at 340°C and stress-annealed thereafter 1h at 340°C with longitudinal applied tensile-stress of 400 MPa), we obtained [10] an increase of the sensitivity to 50 μV/nT and 75 μV/nT, when the excitation frequency was 46.1 kHz and 42.9 kHz, respectively. The transfer characteristic of the sensor, obtained in the field range from -60 μT to +60 μT is linear from –40 μT to +40 μT. The negative feedback increases the linearity domain of the transfer characteristic. Measurements of the magnetic noise level of the sensor show 1.3 nT_{vv}, measured in the magnetometer pass-band of 0-10 Hz.

The results obtained with regard to the miniaturization of direct driving fluxgate sensors are in agreement with the metrological requirements of the devices used for electromagnetic pollution measurements. Using suitable heat treated (pre-annealed 1h at 340°C and stress-annealed 1h at 340°C with longitudinal applied tensile-stress of 418 MPa) $Co_{68,25}Fe_{4,5}Si_{12,25}B_{15}$ amorphous ribbons 0,3 mm wide and 25 μm thick, two sensors which compete favourably with traditional fluxgate sensors with respect to simplicity, miniaturization, sensitivity and noise level are developed: one sensor with the dimensions of 10 x 5 x 2 mm having the sensitivity of 20 μV/nT and the other one with a ribbon 26 mm long, 0.3 mm wide and 25 μm thick as sensing element, having the sensitivity greater than 30 μV/nT. The best results are obtained for hairpin shape of core. The transfer characteristic of the sensor is linear in the field range from –10 μT to +10 μT, but the negative feedback increases the linearity domain (Fig. 3).

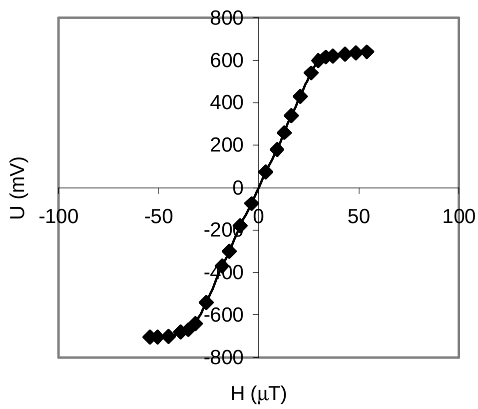

Fig. 3. Transfer characteristic of a direct driven miniature sensor having optimal heat treated $Co_{68,25}Fe_{4,5}Si_{12,25}B_{15}$ ribbon as core.

The possibility to use the developed sensors based on $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous ribbons to measure AC magnetic fields up to 200 μT in the frequency range 0 – 20 kHz was demonstrated [11].

4. Discussion

The functional behaviour of the developed sensors can be discussed in terms of the magnetization processes that take place in the stress annealed amorphous core. The core materials for fluxgate applications should be magnetically soft so that low excitation currents can produce the saturation. If the easy magnetization axis is parallel with the applied field, domain wall movements dominate the magnetization process. This is the case for the as-quenched core (Fig. 2a) where the core axis is the easy magnetization axis. Domain wall movements dominate the magnetization process and a large Barkhausen noise is expected and confirmed by the noise measurements [4, 13]. The presence of the magnetic anisotropy with the ribbon or wire axis as hard magnetization axis promotes magnetization rotations rather than domain wall movements in the AC magnetization processes in fluxgate sensors [3]. This hard axis appeared during the stress annealing remains the hard magnetization axis if the ribbon or wire is cooled to room temperature under applied tensile stress. The more we stabilize by pre-annealing the amorphous structure in the sample, the larger is the induced anisotropy. By the change of the magnetic anisotropy from the easy-core-axis to the hard-core-axis [1, 14] the Barkhausen noise in core material is reduced so that mainly the rotations of the magnetization are responsible for magnetic behaviour of the amorphous core. The effect depends on stress-annealing conditions and is also related to the magnetostriction coefficient value and sign. The hard ribbon axis anisotropy can be induced by tensile stress annealing of the ribbons with positive λ_s. Taking into account that for Co-Fe-based amorphous alloys the magnetostriction coefficient changes [15] from a small negative value $-\ 0.08\cdot10^{-6}$ to a small positive value $\lambda_s = +\ 0.1x10^{-6}$ with respect of the Co-Fe ratio, the hard axis appears during the stress-annealing but the effect becomes visible at a certain longitudinal tensile stress, because the induced hard ribbon axis anisotropy K_{an} is proportional to the tensile stress σ_{an}. The axial hysteresis loops of stress-annealed samples confirm this fact. Because the applied heat treatment does not reduce the hysteresis virtually to zero, we concluded that both rotational and domain wall displacement processes compete with each other in the studied amorphous cores depending on the annealing conditions. Measurements of the magnetic noise of the developed sensors confirm this hypothesis.

The results obtained for the magnetic field sensors with bias control are related only to the magnetic susceptibility resonance in amorphous core and the choice of the operational point of the magnetization curve (the used cores are amorphous ribbons in the as-quenched state). We concluded that the resonant behaviour with respect to the bias control can be used as a quickly and precise method in the determination of the magnetic noise of the magnetic material.

In the case of direct driven fluxgate sensors, the results can be discussed in the term of the contribution of both the stress annealing and the driving magnetic field H_d to the magnetization processes. When a current flows through the wire, it will set up a circular magnetic field which will force the formation of a single magnetic domain in one half of the hairpin shaped wire and another magnetic domain in the other half of the wire. If the current density j is assumed to be constant across the wire, the maximum value of the circular magnetic field induced by the AC electric current passing through the wire (driving magnetic field) is given by $H_d = j\ R/2$, where R is the wire radius. This field will determine a more rectangular form of the circular hysteresis loop [14], in good agreement with the change of magnetic anisotropy from the easy-wire-axis type to the hard-wire-axis type. Therefore, the Barkhausen noise in core material would be reduced.

The good sensor sensitivity obtained at high frequencies of the driving current can be explained by the fact that the domain wall movements are effectively damped at high frequencies so that mainly rotations of magnetization are responsible for magnetic behaviour of the amorphous core. More similar studies in amorphous wires and detailed theoretical calculations will be performed to clarify this point.

5. Conclusions

$Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous alloys in the shape of ribbons and wires as sensing elements were used to develop three types of fluxgate sensors: classical Vacquier-Foerster sensors, Vacquier-Foerster sensors with bias control and direct driven fluxgate sensors.

Tensile stress annealing experiments with $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ ribbons and wires show that it is possible to induce hard axis anisotropy in these cores. Rotational and domain walls displacements processes compete with each other and take place depending on the annealing conditions.

For fluxgate applications, the presence of hard core-axis anisotropy induced in amorphous cores by tensile stress annealing and/or by the driving magnetic field, determines a magnetization process dominated by coherent magnetization rotation and a low Barkhausen noise is obtained.
The results are discussed in the term of the contribution of both the stress annealing and the driving magnetic field at the magnetization processes that take place in the used amorphous cores.

The measured functional parameters of the developed sensors prove that the stress annealed $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous ribbons and wires are able to produce very good quality fluxgate sensing elements. The good mechanical properties, the magnetic behaviour after stress annealing, the low cost of the $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous alloy recommend it for the manufacture of different fluxgate sensors used in magnetometers for both continuous and alternating magnetic field measurements, especially for electromagnetic pollution measurements.

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