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An invariant magnetoimpedance element for stray fields detection

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Abstract

Magnetoimpedance sensitive element that consists of one FeNi[125 nm]/Cu[3 nm])3FeNi[125 nm]/Cu[500 nm]/(FeNi[125 nm]/Cu[3 nm])3/FeNi[125 nm] multilayered structure was designed for the magnetic field detection in the wide range angular interval and its magnetoimpedance was measured experimentally. Double rectangle sensitive element with improved performance was proposed on the basis of mathematical modelling. This simulation was used for optimizing the topology of a wide angle magnetic field sensor equipped with a sensitive element that consists of two crossed multilayered stripes. The creation of magnetoimpedance element, where the measuring response is independent or only slightly dependent on the angle of application of the external magnetic field-is an necessary requirement for the techniques of detection stray fields of complex configuration with unpredictable dynamics.

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Keywords: Magnetoimpedance effect; Thin films; Flexible substrates; Magnetic anisotropy; Microdevises

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1. Introduction

Magnetodynamics of materials with high magnetic permeability is a hot multidisciplinary topic of physics of magnetic phenomena, polymer chemistry/colloidal systems, electronics and biomagnetism Llandro (2010) et al. and Antonov et al. (1997). One of the fast growing branches of this area-the giant magnetoimpedance (GMI) Makhotkin et al. (1991) and Kurlyandskaya et al. (2000). GMI phenomenon consists in the change of the total impedance of the ferromagnetic conductor under application of the external magntetic field Antonov et al. (1997) and Correa et al.

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(2010). Presently, in the thin film shaped samples, which are the most compatible with semiconductor electronics, the achieved sensitivity can be as high as 200%/Oe being sufficient for detection even magnetic fields of biogenic nature. It was already shown that GMI detectors can be used for evaluation the total stray field ensemble of superparamagnetic particles distributed on the surface of GMI element, including both "free" magnetic labels and immobilized magnetic labels configurations by Yuvchenko et al. (2014). This opens the possibilities of GMI application in the field of biosensing and as an instrument for characterization of polymer systems and biocomposites containing magnetic elements with different aggregation features. On the other hand, there is a need of thorough control of external magnetic fields of different configurations for environmental protection both living systems and medical equipment. Therefore, special efforts were made for the creation of particular kind of magnetic field sensors and one of them is wide-angle magnetic transducer. Up to now the main results were obtained for amorphous ribbon based sensitive elements Volchkov et al (2009) and Volchkov et al (2013). This option is very attractive for cheap sensitive elements working at reasonably low frequencies of the order of 5 MHz. At the same time the main disadvantage of the ribbon-based GMI sensitive elements is a big size (at least of the order of 50 mm).

In the present work, a giant magnetoimpedance sensitive element that consists of one FeNi-based multilayered structure was designed with the focus on the magnetic field detection in the wide range angular interval. Double sensitive element with improved performance was proposed on the basis of mathematical modeling based on the experimental data obtained for single rectangle type GMI sensitive element.

2. Experimental methods

The FeNi[125 nm]/Cu[3 nm])3/FeNi[125 nm]/Cu[500 nm]/(FeNi[125 nm]/Cu[3 nm])3/FeNi[125 nm] multilayered structures were deposited onto glass substrate by rf-sputtering in an Ar atmosphere using metallic masks. The thickness of the permalloy layers was selected on the basis of previous studies aiming to avoid the transition into a "transcritical" state Vas'kovskii et al (1997) and Coïsson et al.(2009) and Svalov et al. (2009). A constant magnetic field of 100 Oe was applied during sample deposition in order to create uniaxial induced magnetic anisotropy and high magnetic permeability to insure high GMI value.

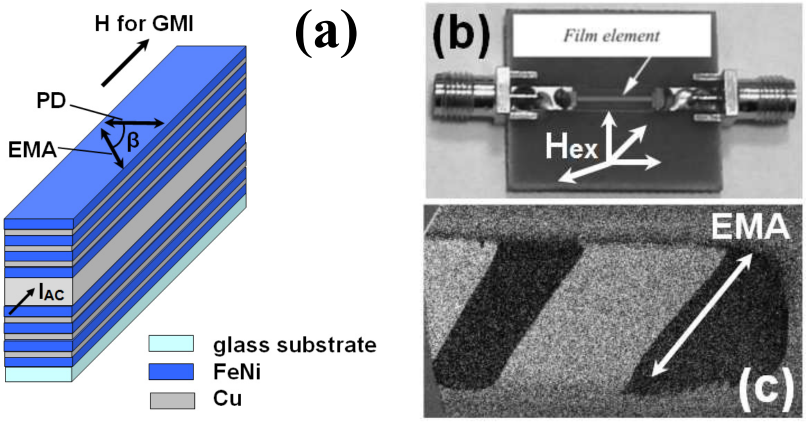

Fig. 1. (a) Schematic description of the structure of the GMI multilayers. [H for GMI] – applied external magnetic field, [PD] – perpendicular direction, [EMA] – Easy magnetization axis, [β] – angle between the direction, which perpendicular of long side of sample and EMA is equal to 45°. (b) GMI sensitive element in the "microstripe" line for magnetoimpedance measurements. The arrows indicate the direction of the external magnetic field Hex. (c) Image of magnetic domain structure obtained by Magneto-Optical Kerr Microscope for GMI rectangular element with 0.5 mm width.

In a majority of GMI studies the easy magnetization axis was usually created in the direction of the long side of rectangular sensitive element Makhotkin,et al. (1991) and Kurlyandskaya et al. (2000). At the same time, for wide angle sensors, that means a need to have reasonably high sensitivity with respect to an applied magnetic field with very weak angular dependence, one can expect better sensor performance in a configuration when easy magnetization axis (EMA) is not perpendicular to the direction of the flowing current and the direction of the external applied field (Figure 1a). In the present study an external magnetic field during deposition was applied under the angle of 45° with respect to the long side of the rectangular sensitive element of 10 mm × 0.5 mm dimensions.

Magnetic domain structure images and quasistatic hysteresis loops were obtained by magneto-optical Kerr effect using Evico microscope: coercivity (Hc) and anisotropy field (Ha) were defined from them. The complex impedance (Z) of the samples was measured as a function of the external magnetic field in “microstripe” line (Figure 1b) using an Agilent Vector Analyzer by the method described in Kurlyandskaya,et al. (2009). The exciting current amplitude w2as 10 mA. The external magnetic field H in the interval +100 Oe to -100 Oe was created by a Helmholtz coils. It was applied along the long side of the rectangular sample.

Magnetoimpedance was measured in the longitudinal configuration, i.e. an external field was applied parallel to the direction of the flowing high frequency current (I_{AC}). The GMI ratio for the total impedance was defined with respect to the maximum applied field Hmax= 100 Oe as follows: $\Delta Z/Z=100 \times (Z(H) - Z(H_{max})/Z(H_{max})$ Complete GMI curve was measured starting from the maximum negative field, the process goes by the “up” branch up to the maximum positive field. Continuing from the maximum positive field, the process goes down to the maximum negative field by “down” branch. GMI sensitivity S was defined as follows: $S(\Delta Z/Z)= \Delta Z/Z/\Delta H$, where ΔH= 0.1 Oe - increment for a magnetic field. The maximum value of $S(\Delta Z/Z)$ for each fixed frequency was denominating as Smax.

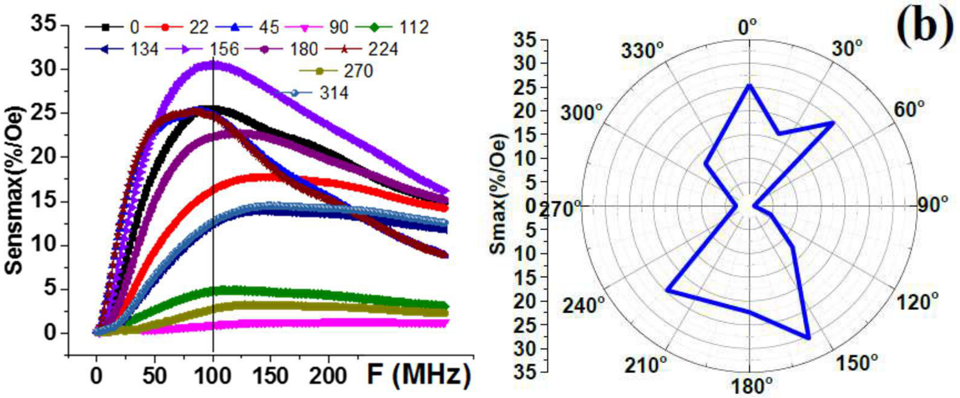

Fig. 2. (a) Frequency dependence of maximum value of GMI ratio sensitivity for total impedance of (FeNi/Cu)3/FeNi /Cu/(FeNi/Cu)3/FeNi element. The different colors of points are equal of various angles of an external magnetic field measured in degree. (b)The angular dependence of maximum ΔZ/Z sensitivity for frequency f=100 MHz

Fig. 2 (a,b) shows frequency dependences of the sensitivity of total impedance ratio ΔZ/Z for $(FeNi/Cu)_3/FeNi/Cu/(FeNi/Cu)_3/FeNi$ sensitive element and angular dependence of maximum ΔZ/Z sensitivity for selected frequency f=100 MHz for which the highest ΔZ/Zmax value was achieved. One can see that the highest GMI ratio does not correspond to direction of the easy magnetization axis (angle of 45 degrees with respect to the long side of rectangular element): the most high ΔZ/Zmax was observed for the angle of 156 degree. This is not too surprising because effective magnetic anisotropy is a sum of different contributions including shape anisotropy which for elongated rectangular element is strongly competing with induced magnetic anisotropy Garcıa-Arribas et al. (2013) and Cortes et al. (2015). Obtained values of the sensitivity up to 20 %/Oe (Fig. 2b) are suitable for applications but one sensitive element of this type seems to be non-suitable for application as magnetic field detection in the wide range angular interval for which constant angular sensitivity is required.

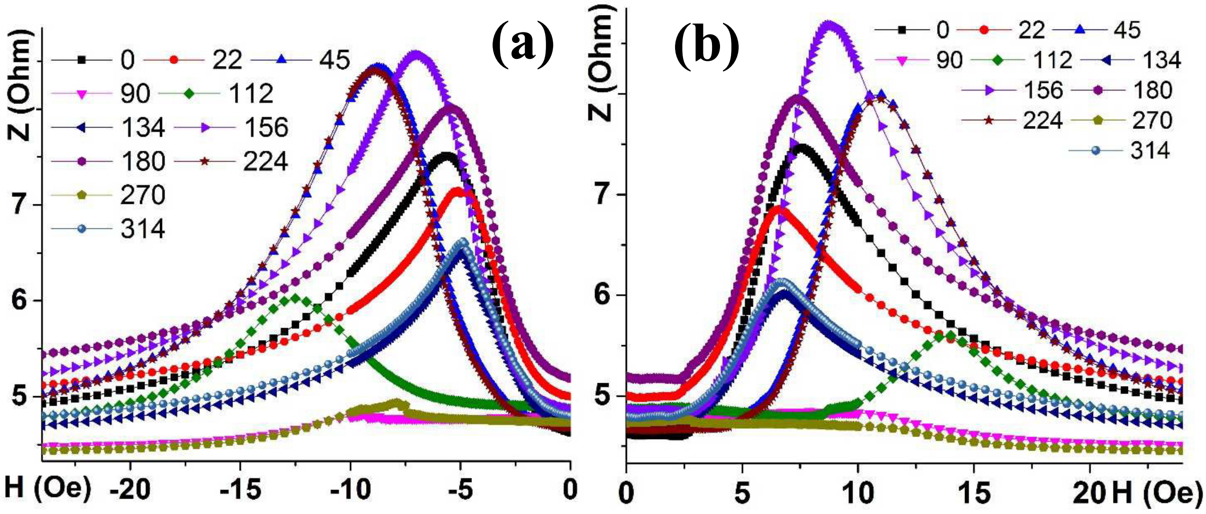

Fig 3. The magnetic field dependences of absolute value of for total impedance of (FeNi/Cu)3/FeNi/Cu/(FeNi/Cu)3/FeNi sensitive element for "down branch": in the positive (a) and negative (b) fields. The different colours of points are equal of various angles of an external magnetic field. Numbers show the values of the angle in degrees starting from the direction parallel to the long side of the rectangular element.

Fig. 3 provides better understanding of GMI behavior in positive and negative magnetic fields. Down branch is analyzed as an example. One can see that both the maximum value of the impedance and the field to reach the maximum value of Z depend on the angle of the external field application. This opens the possibility of an additional control of the sensitive element properties. For example, the highest Z value for positive fields of "down" branch was observed in the field of about 9 Oe and 156º. At the same time if the work point of the magnetic field sensor is a critical parameter one can select 22º angle with still reasonable sensitivity but much lower magnetic field of about 6 Oe to reach this maximum. The difference in the Z(H) curves behavior for positive and negative fields is related to the difference in magnetization processes which a typical for these two fields. They were discussed in the literature in terms for example magnetic phase transitions of different type by Kurlyandskaya et al. (2011). The physics of this phenomena requires additional studies but we will just mention that for practical purposes work points in the positive magnetic fields of "down" branches offer the better values of the sensitivity and work points of the GMI sensitive elements.

Fig. 4 shows the angular dependence of maximum of total impedance Z for frequency F=100 MHz in the reasonably low field of 7 Oe. For the total impedance in this particular case the highest values of Z were observed for 0 and 180º angles but the response was not suitable for the detection of in the wide angular range regime.

Therefore, at the second stage of these studies, in order to decrease the cost and time of the measurements, a mathematical simulation of GMI element based on two crossed multilayered sensitive elements was performed. The simulation of GMI was carried out via the calculation of the impedance change for two crossed thin films elements that form different angles and are connected in parallel under application of an external magnetic field (Fig 4b).

In this paper we proposed only a method of simulation of a wide angle magnetic field sensor based on calculation of two thin films elements which connected as «parallel electronic circuit». The first step was to measure the angular dependence of the impedance and its components of one element for each angle from 0 to 360 degrees. Next, We calculated total resistance, total inductivity and total capacitance in according of the rules of the parallel connection of two resistors, two inductors and two capacitors which are not connected in the middle for each angle. Then, we find the optimum angle for the cross-section of two elements from our database. The angle of 45 degree is the optimal angle from calculation. Generally, we found the two elements-structure with lowest impedance (3 Ohm compared with 7 Ohm in single structure), but with best independence of impedance from the angle and which independence from the hysteresis

The measurements that were performed for a single rectangular GMI element were taken into account during the calculation procedure. The simulation procedure consists in the following. The calculation cycles was performed for a fixed angle of crossing being 45 degree. Fig. 4b shows results of the computer simulation of the angular dependence of the total impedance for the double rectangular GMI element. The performance of the double rectangular sensitive element significantly differ from the GMI response of single rectangle element: impedance value shows symmetric angular dependence with lower variation of the response. Z value changes from minimum value of about 2.8 Ohm for 90 and 270 degrees to the maximum value of about 3.5 Ohm for 0 degree and 180 degrees.

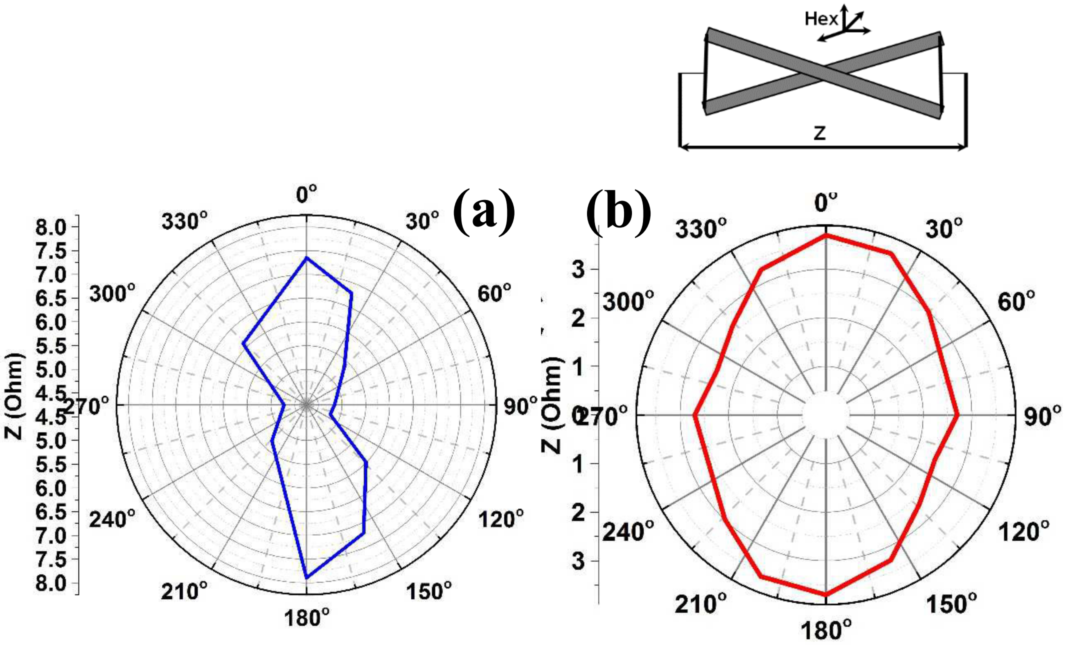

Fig. 4. (a) The experimental angular dependence of an impedance Z in applied external magnetic field of 7 Oe for single rectangular (FeNi/Cu)3/FeNi/Cu/(FeNi/Cu)3/FeNi sensitive element; (b) Fig. 5 The resulting computer simulated dependence of an impedance Z in applied external magnetic field of 7 Oe for double rectangle (FeNi/Cu)3/FeNi/Cu/(FeNi/Cu)3/FeNi sensitive element obtained on the basis of experimental data for single GMI element.

3. Conclusions

The FeNi[125 nm]/Cu[3 nm])3/FeNi[125 nm]/Cu[500 nm]/(FeNi[125 nm]/Cu[3 nm])3/FeNi[125 nm] multilayered structures were deposited onto glass substrate by rf-sputtering in an Ar atmosphere using metallic masks. A constant magnetic field was applied during sample deposition under 45 degrees angle in order to create uniaxial induced magnetic anisotropy and high magnetic permeability to insure high GMI value. In the case of single rectangular GMI element the highest GMI ratio does not correspond to direction of the easy magnetization axis (angle of 45 degrees with respect to the long side of rectangular element): the most high ΔZ/Zmax was observed for the angle of 156 degree. A mathematical simulation of GMI element based on two crossed multilayered sensitive elements was performed. The calculations process was based on the experimental data obtained for GMI response of single rectangle sensitive element. The performance of the double rectangular sensitive element differ from the GMI response of single rectangle element value showing symmetric angular dependence with lower variation of the response. Z value changes from 2.8 Ohm for 90 and 270 degrees to 3.5 Ohm for 0 and 180 degrees.

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